Land quality indicators for sustainable land management: proposed method for yield gap and soil nutrient balance

P.S. Bindraban a,*, J.J. Stoorvogel b, D.M. Jansen c, J. Vlaming c, J.J.R. Groot a

a Research Institute for Agrobiology and Soil Fertility (AB-DLO), P.O. Box 14, NL-6700 AA Wageningen, The Netherlands
b Wageningen Agricultural University, Lab. of Soil Science and Geology, P.O. Box 37, NL-6700 AA Wageningen, The Netherlands
c The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), P.O. Box 125, NL-6700 AC Wageningen, The Netherlands

Abstract

The required increase in agricultural production to meet future food demand will further increase pressure on land resources. Integrative indicators of the current status of the agricultural production capacity of land and their change over time are needed for promoting land management practices to maintain or improve land productivity and a sustainable use of natural resources. It is argued that such land quality indicators should be obtained with a holistic systems-oriented approach. Two land quality indicators are elaborated that deal with (1) yield gaps, i.e. the difference of actual yield and yield obtained under optimum management practices, or yields determined by the land-based natural resources, and (2) a soil nutrient balance, i.e. the rate with which soil fertility is changing. The yield gap is based on the calculation of land-based cereal productivity at three different levels in terms of potential, water limited, and nutrient limited production, considering weather, soil and crop characteristics. These modelled production levels do not incorporate socio-economic aspects, which may impede agricultural management in its effort to release stress because of inadequate soil fertility, water availability and/or occurrence of pests and diseases. Therefore, location specific actual yield levels are also considered. Besides an evaluation of the actual status of the land, it is important to consider the rate of change. The quantification of changes in soil nutrient stocks is crucial to identify problematic land use systems. The soil nutrient balance, i.e. the net difference between gross inputs and outputs of nutrients to the system, is used as measure for the changes. The indicator for the soil nutrient balance combines this rate of soil nutrient change and the soil nutrient stock. Indicators for yield gaps and soil nutrient balances are defined, procedures for their quantification are described and their general applicability is discussed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Land productivity; Soil fertility; Systems approach; Modelling; Yield gap; Soil nutrient balance; Land quality indicator

1. Introduction

World agricultural production has to triple over the coming three to four decades to meet growing food demand, due to increasing population and changing consumption habit (WRR, 1995). Only a quarter of the world food production increase in the past three decades resulted from expansion of agricultural land and the remainder from increase in yield per unit area (IFPRI, 1994). Future area expansion is not desirable, because in many cases this will imply the cultivation of fragile lands. Therefore, an increase in food production will have to come from increased productivity (Alexandratos, 1995). However, at the same time soil nutrient depletion and other forms of soil degradation threaten future soil productivity.

Farmers, researchers and policy makers are interested in integrative measures of the current status of
land quality and its change over time. Land quality refers to the condition and capacity of land, including its soil, weather and biological properties, for purposes of production, conservation and environmental management (Pieri et al., 1995). Maintenance of the agricultural production capacity of land resources is a fundamental element in the discussion on sustainable land use. Changes in land quality should be monitored to provide early warning of adverse trends and to identify problem areas. Monitoring land quality and promotion of land management practices that ensure productive and sustainable use of land resources require development of quantitative land quality indicators (LQI) (Pieri et al., 1995).

With respect to agriculture, quantitative measures of the production capacity of the land that reflect soil and climatic conditions are useful LQIs. A land-based productivity is reached when the available natural resources (radiation, temperature, water and nutrient) are used in an optimal and sustainable manner. To describe this productivity, we calculate yield levels that are determined by weather, water and nutrients. The basic principle to calculate crop production is the concept of stable efficiencies of use of radiation, water (Monteith, 1990) and nutrients (Sinclair, 1990).

Dwindling soil fertility has become an increasingly urgent problem in tropical agriculture, an observation confirmed by farmers, researchers and policy makers. Agro-ecosystems with negative nutrient balances have become widespread, ranging from the low-input food crop areas in the Sahel to the relatively well-endowed volcanic zones of east Africa and Latin America (Stoorvogel and Smaling, 1998). The quantification of changes in soil nutrient stocks is crucial to identify changes in land resources.

This paper deals with the quantification of yield gaps and soil nutrient balance, at the regional, national and continental level. Indicators for both characteristics are defined, procedures for their quantification are described and their general applicability is discussed.

2. Premises for the development of land quality indicators

Ideally, an indicator of land quality represents a generic directive for the functional role of land. A LQI integrates factors and processes that determine land quality. It should allow monitoring of changes in quality over time, and should be applicable at different scales. A LQI with these characteristics can only be obtained with a holistic systems-oriented approach whereby the land use system is mechanistically described. Weather, soil and relevant crop and animal characteristics determine the biophysical production potential of land. Agricultural management, resulting from prevailing socio-economic conditions, in combination with the biophysical conditions, determines the actual production. The characteristics interact with each other and each characteristic has its own particular temporal behaviour. Integration of the underlying processes is needed for the assessment of the agricultural production capacity. Models are a convenient tool for such an analysis. This holistic modelling approach has proven to be useful to analyse agricultural production systems in a quantitative way, enabling objective comparison of production systems in different agro-ecological zones (Rabbinge, 1995). Lack of appropriate data may seriously constrain this approach when it is applied at regional, continental or global scales. The advantages of the modelling approach should be exploited, however, while making maximum use of the limited amount of data available, in determining procedures to define LQIs.

Considering the wide range of activities in agriculture, LQIs with general applicability need to be developed. A yield gap, typically, will be specific to a certain cropping activity. Given the importance of cereals for human diet and the world agricultural production (Goudriaan et al., 1999), cereal yields are appropriate characteristics for defining a quantitative indicator for the production capacity of land. Calculated production figures, expressed as ‘grain equivalents’, result in a good integrator of soil and weather characteristics, allowing comparison of agricultural production potentials under various conditions.

Land quality is dynamic and continuously changing as a result of, e.g. agronomic activities and weather. While land quality indicators can be monitored to quantify their temporal variation, it is also possible to quantify the rate of change. This would allow assessment of future changes in land quality and more strongly support the development of early warning systems. In this study, the dynamics in soil fertility are quantified by estimating the rate of change in terms of the soil nutrient budget.
3. Defining and quantifying land quality indicators: yield gap and soil nutrient balance

3.1. Yield gap

Many processes affect crop performance, but relatively few have a major impact, such as processes resulting in the stable efficiency of the use of radiation, water and nutrient for crop growth (Monteith, 1990; Sinclair, 1990), those contributing to the soil water balance and those affecting soil fertility. Crop growth has been modelled successfully as a function of environmental factors using the concept of these stable efficiencies (Bindraban, 1997). Generic descriptions of soil water dynamics for generalised soil profiles allow good estimates of water availability. Nutrient availability can be assessed through transfer functions and expert judgement from soil characteristics. Crop production can be described for these levels of availability in terms of potential and water or nutrient limited production (Fig. 1). The most suitable cereal crop (depending on the agro-ecological conditions wheat, rice, maize, millet or sorghum) is taken as a proxy for a wide range of crops that could be grown, with yields expressed in ‘grain equivalents’. In practice actual production levels may differ from these calculated levels due to deviant agricultural management. Actual yield is a function of biophysical as well as socio-economic conditions.

3.1.1. Potential production

Crop production under optimum management conditions, i.e. adequate supply of water and nutrients and crop protection, is determined by absorbed photosynthetically active radiation. The foliage of the crop determines which fraction of the daily radiation is absorbed. This absorbed radiation is converted into biomass with a crop specific conversion efficiency (Monteith, 1990). Growth is calculated on a daily basis for the duration of a growing period by a simple deterministic simulation model. Temperature drives crop phenological development and, therefore, determines the growth duration. Temperatures at which growth is feasible determine the length of growing seasons. Multiple cropping is allowed when permitted by climatic conditions. Daily or monthly data on radiation and temperature are required to assess this production level.

3.1.2. Water limited production

The necessary amount of water to fulfil transpiration requirements for crop growth under optimum
management conditions, can be calculated on the basis of crop specific transpiration coefficients (Monteith, 1990). When water supply through rain or irrigation is insufficient, soil water content may fall below a threshold and actual crop transpiration becomes less than potential, proportionally decreasing crop growth. Water availability to the crop is estimated with a capacity type, dynamic soil water model. Infiltration depends on the soil-specific infiltration capacity, the amount and intensity of rainfall and the slope of the terrain. Drainage occurs when field capacity is exceeded and when the soil specific capacity rate allows it. The water-holding capacity of soils is related to soil texture. Soils are variable in depth. Nutrient availability is assumed not to limit crop growth at this production level. Required data to assess this production level, in addition to radiation and temperature, are rainfall and physical characteristics of the soil concerning infiltration and drainage of water, water holding capacity and slope.

### 3.1.3. Nutrient limited production

A quantitative evaluation procedure of the native fertility of soils is available that interprets soil fertility as the capacity of a soil to provide plants with nitrogen, phosphorus and potassium (Jansen et al., 1990). The potential supply of N, P and K from the soil is estimated from a set of chemical properties of the soil. The actual uptake of each nutrient is estimated, taking into account the potential supply of the other nutrients. Subsequently, a nutrient limited yield is determined on the basis of the actual uptake of the nutrients. Required data to assess this production level are the soil chemical characteristics, organic matter, pH, P-Olsen and exchangeable K.

### 3.1.4. Actual yield levels

Actual yield levels are not only influenced by land-based natural resources, but also, and often even stronger, by socio-economic conditions. Cultivation practices are based on farmers’ knowledge and skills, access to markets, land tenure, etc. These practices may not meet the agronomic conditions needed to realise potential yield levels for prevailing eco-physiological conditions. Yields may differ for a multitude of reasons, resulting in sub-optimal use of land resources or even deteriorating the resource base.

![Fig. 2. Visualisation of the three yield levels distinguished to define the nutrient (A), water (B), and potential (C) yield gap, land quality indicator.](image)

#### 3.1.5. Yield and yield gap indicators

The LQI yield gap indicates in a quantitative way the increase in yield that can be obtained under specifically defined management practices over the current yield levels. Consequently, the various calculated yield levels mentioned in the previous section are considered in defining the gaps in yield with actual yield levels (Fig. 2). These yield gaps typically reveal technically feasible options to increase yield. The potential yield gap indicates the highest yield increase that could be obtained when optimising agronomic practices, i.e. with complete and timely protection, and application of water and nutrients. In principle, the same considerations apply to the water and nutrient yield gaps, except that irrigation, respectively, fertilisation is not applied.

### 3.2. Soil nutrient balance

Several approaches are available to study soil nutrient balances. The most appropriate approach is strongly governed by objectives and relates to the spatial scale. The nutrient balance follows from the difference between inputs and outputs. It should be recognised that different production systems may lead to different forms of imbalances, causing problems of completely different character. Agricultural practices with high external inputs, e.g. in Europe, result in positive soil nutrient balances leading to pollution of ground and surface waters. Agricultural practices with low external input, as frequently found in tropical countries, may result in the depletion of soil nutrient stocks, seriously threatening future agricultural production, like in many African countries (Stoorvogel and Smaling, 1990).

Following Stoorvogel and Smaling (1990), the soil nutrient balance is quantified by the estimation of
different nutrient flows. Five major inputs (In 1–5) and five major outputs of nutrients (Out 1–5) were identified (Table 1). The net soil nutrient budget (NSNB) can be determined by calculating the net difference between the inputs and outputs of nutrients expressed in kg nutrients integrated over a certain area and time:

$$\text{NSNB} = \int_{\text{area}} \int_{\text{time}} \left( \sum_{i=1}^{5} \text{In}_i - \sum_{j=1}^{5} \text{Out}_j \right)$$ (1)

The quantification of the individual flows of the soil nutrient balance, i.e. In 1–5 and Out 1–5, requires different approaches. The input data used depends very much on the scale of analysis and data availability. Although data on, for example, crop production are incorporated in national statistics and/or regional databases, a number of required management data as well as values for leaching are typically not known. These data can be estimated using transfer functions. A general description for the different flows follows below.

Nutrient inputs from mineral fertiliser (In 1) can be derived from agricultural statistics or obtained from surveys, depending on scale level. Dissaggregation of those figures for different land use systems might be necessary. Inputs from manure and other organic fertilisers (In 2) depend on prevailing livestock management systems. Deposition by rain and dust (In 3) is generally not readily available, but transfer functions have been derived based on precipitation (Stoorvogel and Smaling, 1990). Nitrogen fixation (In 4) is estimated as a fixed percentage of the total nitrogen uptake of leguminous crops and depends on the cropping pattern. Additionally, crops benefit from small amounts of nitrogen, which are fixed non-symbiotically. Sedimentation (In 5) is relevant only to areas that are naturally-flooded or irrigated. Naturally flooded areas are assumed not to be depleting. Irrigated areas have a fixed input for sedimentation.

Nutrients in harvested products (Out 1) are derived from crop specific nutrient contents and yield obtained from agricultural statistics. Removed crop residues (Out 2) are related to production figures whereby a certain amount of residues is left in the fields. Leaching (Out 3) applies to nitrogen and potassium and is correlated with soil fertility, fertiliser application, crop nutrient uptake, soil clay content and precipitation (Stoorvogel and Smaling, 1990). Gaseous losses (Out 4) are related to the same factors as leaching. Nutrient losses through soil erosion (Out 5) are obtained by multiplying soil loss with soil nutrient content. An enrichment factor is applied to account for the difference in nutrient content between the sediment and the original soil material.

The loss of nutrients as calculated by the NSNB as such is not sufficient to define an indicator for the sustainability of agricultural systems. In Fig. 3, the effect of similar rates of soil nutrient depletion on a fertile (soil A) and an infertile soil (soil B) are schematically presented. The shaded area represents soil nutrient stocks with concentrations that are limiting for crop growth. Although both soils have similar soil nutrient depletion rates, soil B will arrive at a nutrient limiting situation in the near future whereas it will take a long time for soil A to arrive at the same nutrient limitations. The indicator for soil nutrient depletion will, therefore, incorporate both the rate of soil nutrient depletion and the soil nutrient stock (Table 2).

3.3. Data requirements and spatial aspects

Data on weather, soil, crops and crop management is required for the calculation of the various yield levels and the nutrient flows. Not all required data may be readily available in existing databases. Interpol-
Table 2
Nutrient balance land quality indicator: qualitative classification of soil nutrient depletion in relation to soil nutrient stock* 

<table>
<thead>
<tr>
<th>Soil nutrient stock</th>
<th>N–P depletion</th>
<th>Very small</th>
<th>Small</th>
<th>Moderate</th>
<th>Large</th>
<th>Very large</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very low</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Very High</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

*0–5: nutrient depletion almost negligible compared to soil nutrient stock: no effects to be expected in the future; 6: extremely high nutrient depletion therefore immediate action required.

Table 3
Required data for the calculation of land quality indicators yield gap and soil nutrient balance and data sources at a national level*

<table>
<thead>
<tr>
<th>Databases</th>
<th>Weatherb</th>
<th>Soilc</th>
<th>Land cover/use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly temperature (min/max)</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily radiation</td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily temperature</td>
<td>I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monthly rainfall</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily rainfall</td>
<td>G</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Slope</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Soil depth</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Drainage</td>
<td>T</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Soil water holding capacity</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil organic C</td>
<td>T</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>CEC</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-Olsen</td>
<td>E</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>P-fixation</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exchangeable K</td>
<td>E</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>PH</td>
<td>T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural land</td>
<td>D</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Land use</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertiliser use</td>
<td>E</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual yield levels</td>
<td>D/E</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* D: directly obtained; I: interpolated; G: generated; T: transfer; E: estimated.


tinguished. Slope, texture and depth can be directly obtained and the soil water holding capacity is derived from these characteristics (Batjes, 1997) to determine the availability of water to the crop. Soil chemical characteristics have also been related to soil map units using the WISE-database (Batjes, 1997). Soil nutrient availability can either be directly obtained from this source or derived using transfer functions.

The FAO provides data on production areas, yields, fertiliser inputs and agro-climatic maps that are used for the calculation of the NSNB at higher scale levels. At lower scale levels, national databases can be used to fulfil the data requirements. The quality and amount of data varies per country. As a result, the level of detail in the procedure that can be reached is highly variable.

To address the spatial aspect of the LQI, yield levels and NSNBs are calculated for the smallest homogeneous unit, e.g. 0.5×0.5 degree grid basis for the yield gap analysis and for land use systems for the NSNB. Data may have to be aggregated or disaggregated to obtain required characteristics for a unit. Depending on the type of data, weighing procedures can be applied for aggregation purposes. For analysis on a grid basis, interpolation techniques are required to assign values for parameters to areas between observation points, like meteorological stations.

4. Discussion

The methodology for the calculation of yield gaps and nutrient budgets aims to extend knowledge and information from micro and site-specific level to practical and generally applicable indicators at various scales. An explicit description of the agricultural production system, i.e. generic cereal production, governs the calculation procedure, which has been simplified to deal with all scale levels, but remains a holistic, systems analytical approach. Necessary data, even at higher spatial scales, can be found in existing databases. Lack of data should not limit us from attempting to assess LQIs and can be circumvented by explicitly described methods to convert generalised and often qualitative information into quantitative data. This approach reveals gaps in our knowledge, and more importantly, indicates what type of quantitative data are strongly needed. Approaches that use the availability of data as a starting points lack this strong ability to indicate knowledge and data gaps.

The methodology should also allow comparison between agro-ecological zones. Various crops can be grown in numerous ways on agricultural land. Comparison in terms of production capacity is only possible when expressed in one general term. Cereal grain equivalent is most suitable, as many species can grow on the majority of global agricultural land, and because of its importance for human consumption. For similar reasons grain equivalents have also been used in other studies (WRR, 1995). Grain equivalents facilitates comparison between zones, but cereal performance might distort options for improvement when the main agricultural production consist of crops strongly differing from cereals, such as tree crops or cash crops like coffee and tea. Moreover, pests, diseases or weeds can reduce overall crop performance. The impact of biotic stresses ranges from very heavy to virtually non-existent, depending on the environment and management practices. As these biotic stresses are not necessarily land-related, they are not considered in the definition of the land quality indicator yield gap. Interaction effects between water and nutrients have also not been considered. Some overestimates may result from this simplification.

The accuracy of quantification depends on the scale level, whereas it is governed by the objectives of the procedures. Generally, indicators become of a quantitative nature with more detailed scale level. Table 4 presents several examples where soil nutrient balance value have been quantified at different scales. At a continental scale, broad, qualitative classes create awareness. With a number of general classes, problem areas can be identified at a country level to focus research and target specific action. At more detailed scale levels, e.g. community level and farm level, planning and actions against undesired developments, like depletion of soil nutrient stocks, plays an important role on the sustainability of agricultural production systems.

Yield gaps and nutrient budgets are, consequently, indicative, and should not be seen as hard data. The gap in yield between actual and potential yield indicates the impact that efforts to improve land quality can have on productivity increases, but does not indicate the required inputs in terms of water and nutrients. A large yield gap does not necessarily indicate a good return on investment. It is, therefore, important that
Table 4
Examples of the purpose of the soil nutrient balance LQI at different scale levels

<table>
<thead>
<tr>
<th>Scale</th>
<th>Objectives</th>
<th>Detail</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continent</td>
<td>Create awareness</td>
<td>Broad qualitative classes</td>
<td>Stoorvogel and Smaling, 1990</td>
</tr>
<tr>
<td>Country/district</td>
<td>Identification of problem areas to focus research and target specific action</td>
<td>Qualitative classes</td>
<td>Smaling et al., 1993</td>
</tr>
<tr>
<td>Community level</td>
<td>Discussion around the sustainability of agricultural production systems</td>
<td>Nutrient losses in kg/ha, year</td>
<td>Van der Pol, 1993</td>
</tr>
<tr>
<td>Farm level</td>
<td>Development of alternative, more sustainable production systems</td>
<td>Nutrient losses in kg/ha, year (considering only management related flows)</td>
<td>DeFour et al., 1996</td>
</tr>
</tbody>
</table>

estimates are made of the required amount of input of the factors water and nutrients that are required to increase yield. Our procedure allows assessing the impact of management practices on nutrient budgets and land productivity.

The gaps in yield between actual, and water and nutrient limited yield require careful interpretation. Actual yields below the lowest of water and nutrient limited yield levels could indicate sub-optimal use of natural resources. Soil nutrient depletion could range from none to severe, but soils may even be enriched when external inputs are applied. On the other hand, actual yields exceeding the water or nutrient limited yield levels do not necessarily indicate that natural resources are overexploited. External inputs may be sufficiently supplied to the production system. This aspect can be further investigated by assessment of the yield level in dependence of actual external inputs, considering eco-regional specific land characteristics. Any gap occurring with actual yield is a more realistic indicator for the sustainability of the actual production system. In case of fertilisation, for instance, actual yield being less than these input-yields, e.g. due to disease infestation or other improper management, could indicate an enrichment of soils, or a heavy environmental load caused by loss of nutrients. Higher actual yields, on the other hand, could indicate nutrient mining. These possibilities have been presented schematically in Fig. 4. An integrated analysis of yield gaps and nutrient balances could indicate which process is likely to occur. A challenging option for future analyses.

LQIs that are not confounded with social-economic constraints reveal promising areas to obtain increase in yield. Production capabilities can be determined for various levels of management differing in irrigation, fertilisation and crop protection. Availability of geo-referenced data makes it possible to indicate these options on a regional basis. Caution is needed when data are aggregated. Yield gap indices assessed at a grid cell resolution allow visualisation of regional differences within countries. Averaging yields at country level will conceal these differences and hence, opportunities for improvements. Ideally, comparison with actual yield levels should be done at the same resolution as for the calculation units. Country average yield data are comparably non-informative to indicate options for improvements, while data on actual yield levels will not be available at the required resolution. Overlays of actual and attainable yield levels need to be made on the basis of intelligent choices on the homogeneity of regions for a required purpose. Comparisons at the level of agro-ecological zones will

Fig. 4. Comparison of expected yield under current external input conditions to actual yields provides valuable information with regard to the impact on the soil and environment. With regard to nutrients, for instance, situation I indicates enrichment of soils or excess emission to the environment. Situation II suggests exploitation of soil nutrients.
more realistically reveal options for improvements. Therefore, unambiguous definitions of agro-ecological zones should be formulated and data should be collected and made available at this level.

An example of a global database (GLASOD), provides estimates of human-induced soil degradation over the past 5–10 years on the basis of expert judgement. These estimates are qualitative and their reliability is rather limited (Oldeman et al., 1991). A disadvantage of this approach is that it does not allow extrapolation into the future and it is not feasible to impose management options to analyse their impact on future degradation rates and changes in land quality. The combination of the proposed process-based approach on assessment of the production capacity of land and the nutrient balance approach has the possibility to analyse the impact of management scenarios on land quality. Uncertainties in our current assessments, to a major extent caused by poor data quality, do not allow analyses for a long term. At present insufficient information and knowledge is available to accurately quantify long term changes in land quality.

5. Conclusions

Land quality indicators should represent a generic description of the functional role of land. Systems approaches that integrate relevant factors and processes, e.g. in models, are a valuable means to derive land quality indicators. Two comprehensive methods using this approach are proposed to calculate a production related yield gap and a soil fertility related nutrient balance. The methodology allows extending knowledge and information from micro-scale to higher scale levels, reveals gaps in our knowledge, and indicates what type of quantitative data are needed for determining land quality indicators. Assumptions in the calculation process are made explicit and can be scrutinised, while the resulting values of the indicators can be evaluated. Interestingly, the combination of these process-based approaches on production capacity and soil nutrients allows analysis of the impact of management scenarios on land quality. Though careful interpretation is required, the results do reveal options to improve land quality and productivity.

References


