Mueller, L., Schindler, U., Mirschel, W., Shepherd, T.G., Ball, B.C., Helming, K., Rogasik, J., Eulenstein, F. and Wiggering, H. (2010) Assessing the productivity function of soils: a review. Agronomy for sustainable development, 30:3. pp. 601-614. ISSN 1774-0746.

This is an Open Access article. It is available at Springer via http://dx.doi.org/10.1051/agro/2009057

Copyright © INRA, EDP Sciences, 2010

http://hdl.handle.net/11262/10587

Deposited on: 10 February 2015

SRUC Repository – Research publications by members of SRUC
http://openaccess.sruc.ac.uk/

Agron. Sustain. Dev. 30 (2010) 601–614
© INRA, EDP Sciences, 2010
DOI: 10.1051/agro/2009057

Available online at:
www.agronomy-journal.org

Agronomy for Sustainable Development

Review article

Assessing the productivity function of soils. A review

Lothar Mueller[1*], Uwe Schindler[1], Wilfried Mirschel[1], T. Graham Shepherd[2], Bruce C. Ball[3], Katharina Helming[1], Jutta Rogasik[4], Frank Eulenstein[1], Hubert Wiggering[1]

[1] Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF) Müncheberg, Eberswalder Straße 84, 15374 Müncheberg, Germany
[2] BioAgriNomics Ltd., 6 Parata Street, Palmerston North 4410, New Zealand
[3] Crop and Soil Systems Research Group, SAC, West Mains Road, Edinburgh EH9 3JG, UK
[4] Julius Kühn-Institut, Bundesforschungsinstitut für Kulturpflanzen (JKI), Institut für Pflanzenbau und Bodenkunde, Bundesallee 50, 38116 Braunschweig, Germany

(Accepted 20 November 2009)

Abstract – The development and survival or disappearance of civilizations has been based on the performance of soils to provide food, fibre, and further essential goods for humans. Amongst soil functions, the capacity to produce plant biomass (productivity function) remains essential. This function is closely associated with the main global issues of the 21st century like food security, demands of energy and water, carbon balance and climate change. A standardised methodology for assessing the productivity function of the global soil resource consistently over different spatial scales will be demanded by a growing international community of land users and stakeholders for achieving high soil productivity in the context of sustainable multifunctional use of soils. We analysed available methods for assessing the soil productivity function. The aim was to find potentials, deficiencies and gaps in knowledge of current approaches towards a global reference framework. Our main findings were (i) that the soil moisture and thermal regime, which are climate-influenced, are the main constraints to the soil productivity potential on a global scale, and (ii) that most taxonomic soil classification systems including the World Reference Basis for Soil Resources provide little information on soil functionality in particular the productivity function. We found (iii) a multitude of approaches developed at the national and local scale in the last century for assessing mainly specific aspects of potential soil and land productivity. Their soil data inputs differ, evaluation ratings are not transferable and thus not applicable in international and global studies. At an international level or global scale, methods like agro-ecological zoning or ecosystem and crop modelling provide assessments of land productivity but contain little soil information. Those methods are not intended for field scale application to detect main soil constraints and thereby to derive soil management and conservation recommendations in situ. We found also, that (iv) soil structure is a crucial criterion of agricultural soil quality and methods of visual soil assessment like the Peerlkamp scheme, the French method "Le profil cultural" and the New Zealand Visual Soil Assessment are powerful tools for recognising dynamic agricultural soil quality and controlling soil management processes at field scale. We concluded that these approaches have potential to be integrated into an internationally applicable assessment framework of the soil's productivity function, working from field scale to the global level. This framework needs to serve as a reference base for ranking soil productivity potentials on a global scale and as an operational tool for controlling further soil degradation and desertification. Methods like the multi-indicator-based Muencheberg Soil Quality Rating meet most criteria of such a framework. This method has potential to act as a global overall assessment method of the soil productivity function for cropping land and pastoral grassland but needs further evolution by testing and amending its indicator thresholds.

soil functions / soil productivity / soil quality / soil structure / soil classification / sustainable agriculture / land rating

Contents

* Corresponding author: mueller@zalf.de

1. INTRODUCTION - THE DEMAND FOR INFORMATION ON THE PRODUCTIVITY FUNCTION OF SOILS

Soils cover most lands of the earth, but regarding their service for humans they are a limited and largely non-renewable resource (Blum, 2006). On the globe about 3.2 billion hectares are used as arable land, which is about a quarter of the total land area (Scherr, 1999; Davis and Masten, 2003). Total agricultural land covers about 40–50% of the global land area (Smith et al., 2007).

The development and survival of civilizations has been based on the performance of soils on this land to provide food and further essential goods for humans (Hillel, 2009). Global issues of the 21st century like food security, demands of energy and water, climate change and biodiversity are associated with the sustainable use of soils (Lal, 2008, 2009; Jones et al., 2009; Lichtfouse et al., 2009). Feeding about 10 billion people is one of the greatest challenges of our century. Borlaug (2007) stated: "The battle to alleviate poverty and improve human health and productivity will require dynamic agricultural development". There are serious concerns that increases of global cereal yield trends are not fast enough to meet expected demands (Cassmann et al., 2003). However, agricultural development cannot be intensified regardless of the bearing capacity of soils, ecosystems and socio-economical environment. It has to be imbedded within balanced strategies to develop multifunctional landscapes on our planet (Wiggering et al., 2006; Helming et al., 2008). Handling of soils by societies must be in a sustainable way in order to maintain the function of all global ecosystems (Rao and Rogers, 2006; Ceotto, 2008; Bockstaller et al., 2009; Hillel, 2009). This includes the use of soils by agriculture for high productivity (Lal, 2009; Walter and Stützel, 2009). Global carbon, water and nutrient cycles are also affected by agriculture (Bondeau et al., 2007).

Soils have to provide several ecological and social functions (Blum, 1993; Tóth G. et al., 2007; Lal, 2008; Jones et al., 2009). Based on a definition of Blum (1993) one of the six key soil functions is "food and other biomass production". The soil protection strategy of the European Commission (EC, 2006; Tóth G. et al., 2007) addresses "biomass production" as a main soil function which must be maintained sustainably. We call this the "productivity function". The productivity function is related to the most common definition of soil quality as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Karlen et al., 1997). Based on this definition, the objective comes close to the assessment of "agricultural soil quality".

Although the productivity function of soils is of crucial importance, it is sometimes ill-defined or its description may be very different. In the German soil protection Act (BBodSchG, 1998) the productivity function is about "utility for agriculture and forestry". Amongst those utility functions (agriculture, resources, settlement and traffic), soils used by agriculture and forestry have a unique position. Firstly, agricultural soils have to be used sustainably to maintain their productivity potential long-term. Secondly, natural soil functions (habitat, nutrient cycling, biofiltering) are not only the domain of soils in natural protected areas. Agricultural soils have to fulfil their natural functions too, e.g. provide or support ecosystem services (Foley et al., 2005). Assessing the productivity function is not restricted to specific land use concepts with regard to management intensity. It embraces the capacity of soils for low-input and organic farming approaches. Also, soils in more natural ecosystems may provide some productivity function. This paper focuses on the productivity function of soil on agricultural land. We shall analyse available methods and tools for assessing the state of soils concerning their ability to provide the productivity function. We consider which evaluation tools are available to quantify soil productivity and which tools are needed to meet further demands under changing climate and soil management. We start from the hypothesis that a growing community of land users and stakeholders has to achieve a high productivity without any significant detrimental long-term impact on soils and the environment. This requires an increasing awareness of a demand to assess the productivity of their soils using internationally standardised frameworks and simple diagnostic tools.

Our focus shall be on answering the following questions:

- Which properties of soils most affect their productivity?
- Which information on soil productivity potentials do existing soil classification systems provide?

- What methods of assessing the productivity function of soils are available?
- How useful are these methods in assessing different aspects of agricultural soil quality?

Conclusions are made for the development of a framework and evaluation tools of agricultural soil quality consistently over different scales as a basis for monitoring and sustainable management of soils.

2. SOILS AND THEIR CONSTRAINTS TO PLANT GROWTH

Soils are components of terrestrial ecosystems. The productivity of these systems is controlled by natural factors and by human activity. Most important external natural factors are solar radiation, influencing temperature and evapotranspiration, and/or precipitation (Lieth, 1975). Soils may provide for plant growth if climate, as the main soil forming factor, is in an appropriate range (Murray et al., 1983; Lavalle et al., 2009). Thus, on a global scale, natural constraints to soil productivity can be classified into three major groups. The first group includes the thermal and moisture regimes of soils. Plants require appropriate soil temperatures and moisture for their growth (Murray et al., 1983; Lavalle et al., 2009). For most soils, thermal and moisture regimes are directly dependent on climatic conditions. They define the frame for limitations like drought, wetness, or a too short vegetation period, limiting the productivity (Fischer et al., 2002).

Worldwide, soil moisture is the main limiting factor in most agricultural systems (Hillel and Rosenzweig, 2002; Debaeke and Aboudrare, 2004; Ciais et al., 2005; Verhulst et al., 2009; Farooq et al., 2009). Drylands cover more than 50% of the global land surface (Asner and Heidebrecht, 2005). Available soil water is a prerequisite for plant growth. In all climates suitable for agriculture, the water storage capacity of soils is a crucial property for soil functionality including the productivity function (AG Boden, 2005; Shaxson, 2006; Jones et al., 2009). It is closely correlated with crop yields (Harrach, 1982; Wong and Asseng, 2006).

The second group of restrictions includes other internal soil deficiencies mainly due to an improper substratum limiting rooting and nutrition of plants. These include shallow soils, stoniness, hard pans, anaerobic horizons, or soils with adverse chemistry such as salinity, sodicity, acidity, nutrient depletion or contamination which may cause severe restrictions to plant growth or the utilisation of biomass (Murray et al., 1983; Louwagie et al., 2009).

The third group includes topography, sometimes considered as an external soil property, preventing soil erosion and providing accessibility by humans and machinery (Fischer et al., 2002; Duran Zuazo, 2008).

There seems to be an interaction between natural constraints to soil productivity and societal factors. Historically, many countries with poor soils tended to be poorly developed. This has led to accelerated soil degradation. Currently, in developing countries, about two thirds of soils have severe constraints to agriculture. Their low fertility (38%), sandy or stony soils (23%), poor soil drainage (20%) and steep slopes (10%) are the main limits to productivity (Scherr, 1999).

3. INFORMATION ON TAXONOMIC SOIL CLASSIFICATION SYSTEMS FOR SOIL PRODUCTIVITY POTENTIALS

Soil classification systems are based on a combination of different criteria. Attributes used for classification may reflect both pedogenesis and pedofunction (Schroeder and Lamp, 1976; Beinroth and Stahr, 2005). Whilst morphological and functional criteria dominated soil classification until the 19th century, pedogenic criteria prevail at higher levels in national soil classification systems since the 20th century (Ahrens et al., 2002; Beinroth and Stahr, 2005). Functional information like the type of substrate is also part of most current soil classifications. In some cases pedogenic and functional criteria are combined, and genetic soil types provide information about soil productivity potentials. For example, Chernozems, which have developed mainly from loessial material and have a mollic epipedon, rich in humus, have a high crop yield potential, whilst Leptosols are shallow soils of low productivity. Podzols are leached sandy soils lacking nutrients and water storage capacity. These examples show that if the soil type or reference soil group is associated with typical substrate and climate conditions, some functional properties may be determinable.

Apart from these extremes, functional information derivable from higher level soil classifications is relatively low. Some soil types or reference soil groups such as Cambisols, Fluvisols or Regosols may have developed from different soil substrates in different climatic environments. In those cases, more relevant information about possible soil productivity at a local or regional scale is provided if the classification includes further soil attributes like texture, organic matter, degree of trophy and pH. Soil texture is correlated with other important functional attributes like water and nutrient storage capacity and thus has become a dominant criterion of all existing functional classification systems since soil began to be managed (Storie, 1933; Rothkegel, 1950; Feller et al., 2003; Beinroth and Stahr, 2005; Begon et al., 2006).

As the USDA soil classification (Keys to Soil Taxonomy, 2006) includes climate information in terms of soil moisture and temperature regime classes, correlations of soils with their productivity at a hierarchy level of great groups (3rd level) are relatively high. In contrast, the FAO soil map of the world and the latest reference base for soil resources (WRB, 2006) lack information about temperature and moisture regimes and thus information on soil productivity potentials. For a rough assessment of soil productivity potentials in Africa, Eswaran et al. (1997) had to translate the FAO soil map of Africa into the USDA soil taxonomy by supplementing climate information.

At the lowest levels of the soil classification hierarchy, functional information on particular soils is greatest. Soils classified at series level in USDA Soil Taxonomy, in the UK soil classification, or local soil types on forest sites in some federal states of Germany, contain detailed information on soil morphological and functional properties, which can be linked with soil productivity data (Mausel et al., 1975; Kopp and Schwanecke, 2003). However, the specific data and correlations cannot be transferred to other regions.

Soil taxonomic classifications sometimes include information on soil structure, which often reflects anthropogenic impacts within human timescales on soil. This information provision can be relatively high with some soils like Histosols in the AG Boden (2005) and Keys to Soil Taxonomy (2006) but it is low with most mineral soils.

4. SOIL STRUCTURE AS A CRITERION OF AGRICULTURAL SOIL QUALITY

Soil structure is a complex category and a key to soil biological, chemical and physical processes (Jackson et al., 2003; Karlen, 2004; Bronick and Lal, 2005; Kay et al., 2006; Roger-Estrade et al., 2009). The spatial arrangement of aggregates and porosity is a main aspect of soil structure. Structure is related to soil function, e.g. to the productivity function or to water and solute transport. Unfavourable structure can result in lower crop yields and greater leaching losses (Kavdir and Smucker, 2005). Current structure features and function result from soil substratum, genetic and management factors. Soil structure is vulnerable to change by compaction and erosion and its preservation is key to sustaining soil function. Crop rotation and tillage strategies should aim to produce optimum soil structure for high and sustainable crop yields (Hulugalle et al., 2007). A good soil structure for plant growth may play a particularly important role in organic farming while poor soil structure cannot be compensated by an extra input of agrochemicals in those systems (Munkholm et al., 2003).

Visible soil structure revealed by digging up the soil shows the abundance and arrangement of soil aggregates and roots which may indicate properties of soils that are dependent on soil management (Shepherd, 2000; McKenzie, 2001; Lin et al., 2005; Mueller et al., 2009). It reflects important aspects of the dynamic indicators of soil quality, indicators that can be categorised and used to monitor and control the status of soil. Farmers and gardeners do this in an individual, experienced-based visual-tactile manner. Visual-tactile recognizable soil features like colour, texture, moisture conditions, earthworm casts may serve to evaluate and classify the quality of soil (Shaxson, 2006).

As indigenous people have done before, soil science and soil advisory services utilise the same common field diagnostic criteria within defined frameworks and check their validity over larger scales. Over the past decades, the interest in soil structure evaluation as a diagnostic tool for assessments of dynamic, e.g management-induced, soil quality has been recognised and has evolved (Shepherd, 2000; McKenzie, 2001; Lin et al., 2005; Shaxson, 2006). Methods of visual soil structure examination enable semi- quantitative information for use in extension and monitoring (Shepherd, 2000; McKenzie, 2001) or even modeling (Roger-Estrade et al., 2004, 2009). One of their advantages is a quick, reliable assessment of good, acceptable or poor states of soil structure. Soil structural features meet the farmer‘s perception on soil quality (Shepherd, 2000; Batey and Mc Kenzie, 2006) and are correlated with measured data of physical soil quality (Lin et al., 2005) and crop yield (Mueller et al., 2009). However, clearly defined rules and scoring methods are necessary to minimise subjective errors.

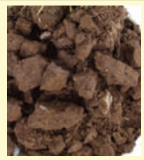
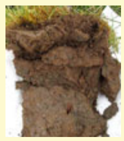
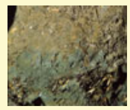
Several methods have been developed over the past five decades. One of the oldest but most accepted methods is that of Peerlkamp (1967). The traditional French method "Le profil cultural" (Roger-Estrade et al., 2004) belongs to a group of more sophisticated methods providing detailed information on the total soil profile. A quantitative comparison of some methods and their correlations with measured physical parameters after standardizing data revealed that most methods provided similar results (Mueller et al., 2009). Types and sizes of aggregates and abundance of biological macropores were the most reliable criteria as related to measurement data and crop yields. Differences in soil management could be recognised by visual structure criteria (Mueller et al., 2009). Unfavourable visual structure was associated with increased dry bulk density, higher soil strength and lower infiltration rate but correlations were site-specific. Effects of compaction may be detected by visual examination of the soil (Batey and Mc Kenzie, 2006).

Visual methods based on, or supplemented by illustrations, have clear advantages for the reliable assignment of a rating score based on visual diagnostic criteria. The latest development of the Peerlkamp method provided by Ball et al. (2007) is well illustrated (Fig. 1). Also, the New Zealand Visual Soil Assessment (VSA, Shepherd, 2000, 2009) as an illustrated multi-criteria method, enables reliable assessments of the soil structure status. These are feasible tools for structure monitoring and management recommendations. However, they may explain only part of crop yield variability, as the influence of inherent soil properties and climate on crop yield is dominant, particularly over larger regions.

5. METHODS OF ASSESSING THE OVERALL PRODUCTIVITY FUNCTION OF SOIL

5.1. Soil and land evaluation in a historical context

In a global context, the utilisation of the soil productivity function in agriculture requires not only soils but also an appropriate climate and human activity. Methods for the evaluation of the potential for the productivity of soil have recently been called "land" evaluation methods. "Land evaluation" has been defined as "the process of assessment of land performance when used for specific purposes (FAO, 1976). Historically, land evaluation has developed from soil science. As soil is the most important component of the land resource, soil evaluation is crucial for land evaluation (Rossiter, 1996). In many cases, there is no clear differentiation between soil and land evaluation (van Diepen et al., 1991; van de Steeg, 2003). Climate as a main precondition for the production of plant biomass varies over larger spatial scales than soil. Approaches to evaluate the productivity potential of soils from a more regional perspective in similar climates (fields, agricultural regions, smaller countries) tend to prefer the term "soil"

Structure quality	Ease of break up (moist soil)	Size and appearance of aggregates	Visible porosity	Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature
Sq1 Friable (tends to fall off the spade)	Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous	Roots throughout the soil			 Fine aggregates
Sq2 Intact (most is retained on the spade)	Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2mm - 7 cm. No clods present	Most aggregates are porous	Roots throughout the soil			 High aggregate porosity
Sq3 Firm	Most aggregates break with one hand	A mixture of porous aggregates from 2mm -10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Some porosity within aggregates shown as pores or roots.	Most roots are around aggregates			 Low aggregate porosity
Sq4 Compact	Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks	All roots are clustered in macropores and around aggregates			 Distinct macropores
Sq5 Very compact	Difficult	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low; macropores may be present; may contain anaerobic zones	Few, if any, restricted to cracks			 Grey-blue colour

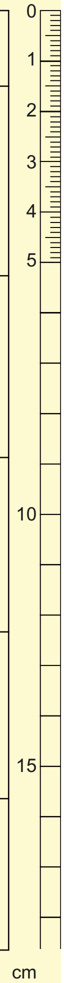


Figure 1. Revised Peerlkamp scale as an example of soil structure evaluation (Ball et al., 2007). The evaluation focuses on aggregates, porosity and roots. Photographs enable a reliable allocation of scores to real visible features of the topsoil. Intermediate scores and layers of differing scores are possible.

for their object of assessment and rating. Approaches coming from a more global perspective (globe, continents, larger countries) tend to emphasise the role of climate and humans in biomass production and favour the term "land". The latter became dominant over the past 40 years, whilst evaluations of the productivity potential of "soil" have a long history, beginning with farming and animal husbandry. Ahrens et al. (2002) stated "…pedology and soil science in general have their rudimentary beginnings in attempts to group or classify soils on the basis of productivity. Early agrarian civilizations must have had some way to communicate differences and similarities among soils." At the beginning of the 19th century the German agronomist A. D. Thaer created a 100 point rating system for the productivity potential of soils based on texture, lime and humus content (Feller et al., 2003). It is one example of a predecessor for some of our current evaluation schemes of agricultural soil quality (Gavrilyuk, 1974; Feller et al., 2003).

5.2. Methods of soil and land rating

5.2.1. Traditional national soil ratings

At national level, specific methods for the evaluation and classification of the productivity potential of soils and land have been developed. In Europe they have existed for about 60–100 years. In many countries they are defined by acts of government, have been done by soil surveys and have a high coverage in terms of mapped areas. Examples of those well known soil and land productivity rating systems at national levels are the Storie Index Rating (Storie, 1933), the German and Austrian Soil Rating (German term "Bodenschaetzung"), (Rothkegel, 1950; Pehamberger, 1992; AG Boden, 2005) and the system of soil rating of the former Soviet Union (Gavrilyuk, 1974). These methods try to cover the overall agricultural land with 100% coverage in some countries and are still applied for different purposes, ranging from land taxation to soil protection planning (Hartmann et al., 1999; Preetz, 2003; Rust, 2006). Ratings of these systems have a 100 point scheme in many cases. Data are ordinally scaled. Some methods have been updated and adapted to altered conditions. A main reason was to provide better correlations with current crop yields. The Austrian Soil Rating was amended by climate factors (Bodenaufnahmesysteme in Österreich, 2001), whilst other systems like the German Soil Rating have remained unchanged for about 80 years.

5.2.2. More recent land evaluation systems at national levels

Over the past 20 years, specific soil and land evaluation systems have been developed or are under construction. Examples of these systems are the US LESA system (Pease and Coughlin, 1996) and the Canadian Land Suitability Rating System for Agricultural Crops (LSRS, Agronomic Interpretations Working Group, 1995). The LESA system consists of a soil evaluation component (Storie Rating) and other factors that contribute to the suitability of land for agriculture, like location, surrounding use and infrastructure. The LSRS system is mainly based on soil attributes and climate factors (Agronomic Interpretations Working Group, 1995). Other countries with substantial agricultural production and fast growing demands like China and Brazil intend to implement quantitative evaluation systems of soil and land productivity (Peng et al., 2002; Bacic et al., 2003; van de Steeg, 2003; Zhang et al., 2004). Also in Russia there are efforts to establish contemporary soil and land information and evaluation systems (Karmanov et al., 2002; Yakovlev et al., 2006). In the Ukraine, Medvedev et al. (2002) developed an evaluation system of the suitability of land for growing cereals based on soil information and climate data. In Hungary, a modern land evaluation system is being established, containing on-line soil evaluation, which is based on the real-time calculation of D-e-Meter soil fertility index using GIS to produce soil maps at a scale of 1:10 000 (Tóth T. et al., 2007).

All these soil and land evaluation systems are specific in approach, data and scale and their outputs are not or only rarely comparable. Approaches that have been developed for larger countries cover a broader variability of soils and climate and seem to have a better potential for evaluation of agricultural soil quality in trans-national studies.

5.2.3. Soil capability and suitability classifications

Besides productivity ratings, in many countries, classifications of agricultural land limitations (steep lands, dry lands, stony lands), or final allocations to categories like “prime farmland” have been mapped. Examples of those national soil and land capability classifications are the US capability classification (Klingebiel and Montgomery, 1961; Helms, 1992), the UK system developed by the Macaulay Land Use Research Institute (Bibby et al., 1991), the New Zealand land use capability system (Lynn et al., 2009) and the soil fertility classes for agriculture in Australia (Hall, 2008).

Those capability classes are nominal, categorical data, useful for land use planning but not for more detailed productivity assessments within these categories. Data of modern national or federal state soil and land information systems provide tailored medium scale capability classifications.

Soil suitability classifications express soil productivity potentials in terms of the possibility of growing specific crops. In the nineteenth century in German states, soil suitability classification systems using classes ranging from “Prime wheat soil” to “Rye soil” or “Oats soil” were common, and were based on work of Thaer and others (Meyers Lexikon, 1925). As requirements of plants regarding the functional status of soil may differ, all recent soil productivity relevant classifications must have a certain stratification or orientation on crops or groups of crops. Cereals are a basic source of human food supply and while they reflect differences in agricultural soil quality, some systems (Rothkegel, 1950; Agronomic Interpretations Working Group, 1995; Mueller et al., 2007) refer to cereals or cereal-dominated rotations. In the UK, soil suitability classifications have been developed for specific purposes such as direct drilling or reduced tillage. Such systems emphasise the limitations of soil structure and drainage status (Cannell et al., 1978). The presence of climatic data within land use capability classification systems means that such systems can accommodate climate parameters projected into the future. Thus climate change scenarios can be used to identify future changes in land capability (Brown et al., 2008).

5.2.4. Global and large regional soil and land evaluations and classifications

The concept of agro-ecological zoning (AEZ) was developed by the International Institute for Applied Systems Analysis (IIASA) and the FAO (Fischer and Sun, 2001). This sophisticated methodology and model provide a framework for the characterization of climate, soil, and terrain conditions relevant to agricultural production. GIS-based suitability classes for estimating specific crops and their yields over the globe have been calculated and mapped from the sub-national to the global level (Fischer et al., 2002). The system processes soil information, including the FAO/UNESCO Digital Soil Map of the World, with climate information playing the most important role.

The Fertility Capability Classification (FCC, Buol et al., 1975) is based on soil survey data and aims to make soil management recommendations and crop yield interpretations. It focuses on those properties and data of soils, topsoils in particular, that are important to fertility management (Sanchez et al., 1982). The system has been mainly applied to the tropics (Sanchez et al., 2003) and updated to a global soil functional capacity classification, providing overviews on single soil constraints to productivity like waterlogging, erosion risk, salinity and others. The basis of both the AEZ methodology and the

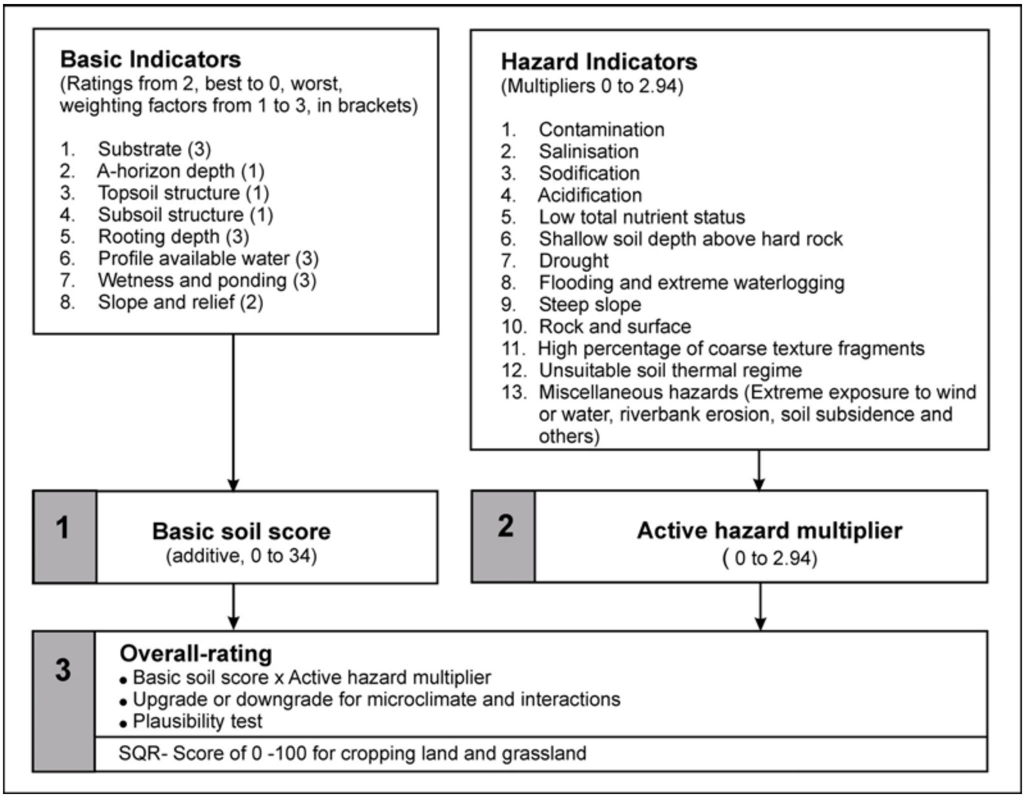


Figure 2. Indicator system of the Muencheberg Soil Quality Rating (Mueller et al., 2007). Indicator ratings of soil states are based on rating tables given in a field manual which also contains, where relevant, hazard indicators and their thresholds. Best soils for cropping and grazing do not have values of hazard indicators which exceed the thresholds.

FCC system are low resolution maps and a limited set of soil parameters and data.

Computer aided land evaluation and classification systems provide capability assessments. MicroLEIS (De la Rosa, 2005) is a system of agro-ecological land evaluation and interpretation of land resources and agricultural management. It has been extended to a decision support system, providing a multifunctional evaluation of soil quality using soil survey input data (De la Rosa et al., 2009).

Crop productivity estimators (Tang et al., 1992) can also be used as research tools and in planning studies. They combine both quantitative and qualitative data to estimate attainable crop yield for different soil units (Verdoodt and van Ranst, 2006). Examples of productivity models with focus on soil erosion are the Productivity Index (PI) model (Pierce et al., 1983), its modifications (Mulengera and Payton, 1999; Duan et al., 2009) and the Erosion Productivity Impact Calculator, EPIC (Williams et al., 1983; Flach, 1986).

The Muencheberg Soil Quality Rating (M-SQR, Mueller et al., 2007) has been developed as a potential international reference base for a functional assessment and classification of soils (Fig. 2). It focuses on cropland and grassland and is based on productivity-relevant indicator ratings which provide a functional coding of soils. Two types of indicator are identified. The first are basic and relate mainly to soil textural and structural properties relevant to plant growth. The second are hazard, relating to severe restrictions of soil function. The sum of weighted basic indicator ratings and multipliers derived from ratings of the most severe (active) hazard indicator yield an overall soil quality rating index. Indicator ratings are based on a field manual and utilize soil survey classifications (AG Boden, 2005; FAO, 2006), soil structure diagnosis tools, and local or regional climate data.

5.2.5. *Models predicting biomass*

There are a large and fast growing number of crop growth and ecosystem models that estimate the local productivity for specific crops, soils and weather data. Models are specific in purpose, vary in their spatial and local scale of resolution, in their focus on particular plants or land use systems, in their proportion and attributes of soil information data and other criteria. These crop growth models can be utilised for assessing the soil productivity for regions where yield data bases exist and the models were parameterised and validated.

On a global scale, modelling climate change relevant issues like possible shortfalls in food production (Tan and Shibasaki, 2003), drought risk (Alcamo et al., 2007), carbon balance (Bondeau et al., 2007) or GHG emissions (Stehfest et al., 2007) requires reliable calculations of the terrestrial biomass, crop growth and yield. Terrestrial biogeochemical models like the Global Assessment of Security (GLASS) model (Alcamo et al., 2007) containing the Global Agro-Ecological Zones methodology of Fischer et al. (2002) may provide this. Models of this group are valid on a global scale, but the spatial resolution is relatively low. They are sophisticated research tools, not designed for local scale calculations or even management decisions in agriculture.

On a daily temporal basis and local scale working crop production and ecosystem models like DAISY (Hansen et al., 1990), the CERES model family (Ritchie and Godwin, 1993; Xiong et al., 2008), WOFOST (Supit et al., 1994; Hijmans et al. 1994; Reidsma et al., 2009), CANDY (Franko et al., 1995), AGROTOOL (Poluektov et al., 2002), SIMWASER (Stenitzer and Murer, 2003), THESEUS (Wegehenkel et al., 2004), the AGROSIM model family (Mirschel and Wenkel, 2007), DAYCENT (Del Grosso et al., 2005), HERMES (Kersebaum et al., 2007, 2008) and many others provide productivity estimates of sites under varying conditions of weather, soil moisture or even soil management status.

Models of this group have in common that they are sophisticated and specific from methodology and design to their purpose and site situation. Their validation requires comprehensive knowledge and data (Bellocchi et al., 2009). They run well in the environment they are created for, but their transferability to other locations, scales or purposes is limited. Their data input demand, effort for soil data adaptation to other environments, and their calculation time is currently relatively high as compared with straightforward soil and land rating approaches of Section 5.2.4. However, because of their sophisticated process-based background and further advances in technology, biomass prediction models have great potentials to serve as reliable and fast decision tools. Their flexibility in handling will remain limited in comparison with simple soil and land rating approaches.

5.2.6. Direct recordings of biomass and crop yield data

Crop yield is a part of the net primary production (NPP) in managed ecosystems. Yield and NPP are often satellite driven, recorded and modelled (Smit et al., 2008; Prieto-Blanco et al., 2009; Kurtz et al., 2009). Also, permanent recording of spatial crop yield data as done in precision farming (Ritter et al., 2008; Schellberg et al., 2008; Lukas et al., 2009) may produce databases which have the potential to predict the productivity of land by statistical procedures of spatio-temporal auto-regressive forecasting, state-space approaches (Wendroth et al., 2003) or combinations of models and data (Reuter et al., 2005; Schellberg et al., 2008). The latter approaches developed for precision farming may provide excellent GIS-based modelling or even forecasting of land productivity in the field and at a regional scale but algorithms are rarely transferrable to other regions. Over larger regions and at a range of scales, the availability of soil survey information has to be taken into account. The combination of soil information systems with recorded crop yield data allows an identification of crop-yield relevant soil properties.

All these approaches represent major areas of soil scientific progress over the past 40 years (Mermut and Eswaran, 2001) but include two common risks of data gathering: at First, the speed in developing algorithms and models often cannot keep pace with the rate of increase of available data. A second implication may be the loss of "ground adhesion", e.g. the difficulty of incorporating large amounts of data and sophisticated models into participatory approaches of decision support and in-situ decision procedures. Soil quality assessments for sustainable land use require straightforward tools, reliable but easy to implement into more complex decision models. Approaches based on simple soil functional classifications which are cross-validated with satellite and aerial data show great versatility for modelling policy scenarios (Baisden, 2006).

5.3. Comparison of methods of soil evaluation relevant to soil productivity

The comparability of soil productivity-related methods for assessing overall soil quality has been evaluated by different criteria including scale of validity, field method capability, reliability, relation to soil and climate data, plant suitability and others. Table I shows a list of criteria applied for the evaluation of the methods. For reasons of overview and readability of the table, only the rating values of a few distinct methods are provided. Values demonstrate that all existing methods have their merits and weakness regarding specific criteria. Figure 3 is an arbitrary similarity–dissimilarity plot by neighbourhood for evaluating systems of soil productivity potentials using a statistical procedure of multi-dimensional scaling (Procedure MDS, SPSS inc., 1993). This plot is a computed map based on extending Table I by including more available methods and weightings of some criteria like performance over scales and correlations with crop yields. Wide separations indicate dissimilarities of methods. This procedure shows clear separation between traditional soil ratings (Storie Index Rating, German Soil Rating and dynamic visual assessments of soil quality (VSA)). The rating system of the former Soviet Union (Gavrilyuk, 1974) is similar to the Storie Index Rating. Crop models and the AEZ methodology are similar both in purpose and in results. They are located far from the centre as these procedures are not field methods of soil assessment and are mainly based on climate information.

Soil data sets (examples: minimum data set of Wienhold et al. (2004), or Cornell soil health test (Schindelbeck et al., 2008), also occupy isolated positions as, although they contain detailed soil information, they do not contain climate information and are based on laboratory analyses.

The soil management assessment framework of Andrews et al. (2004) would also be located in their vicinity. The Canadian Land Suitability Rating System (LSRS), and the Muencheberg Soil Quality Rating, (M-SQR) which include more crop yield relevant parameters (climate, soil structure) are in-between and closer to the centre. While rating procedures are different, inputs are similar. M-SQR indicator ratings are expert based and validated with crop yield data from Germany, Russia and China.

Table I. Evaluation criteria and scheme of some existing methods for assessing overall agricultural soil quality (evaluation numbers 0 = none/false/worse; 1 = low/few/slow; 2 = medium; 3 = high/many/much/fast/good; 3 is always the best rating).

Criterion ↓	Storie index [(1)]	German BS [(2)]	AEZ [(3)]	VSA [(4)]	M-SQR [(5)]
Purpose of method					
Overall soil rating	3	3	0–1	0	3
Capability rating potential	3	0	1–2	0–1	3
Crop suitability rating	0	0	3	0–1	0–1
Tool for soil monitoring	0	0	1	3	2–3
Tool for soil management/extension	0	0	0	3	2–3
Tool for land use planning	2–3	2	3	1	3
Performance in spatial scales					
Field to regional level	3	3	0	3	3
Large regional to nation level	3	3	3	2–3	3
Trans-National	2	1	3	1–2	3
Indicator criteria					
Number of inherent SQ[(6)] indicators [(a)]	2	1	2	0	3
Number of dynamic SQ indicators	0	0	0	2	1
Climate inclusion	0	0	3	0	2
Interactions between indicators considered	0	0–1	2–3	0	0–1
Potential for assessing soil functions other than productivity	1–2	1	1	1	2–3
Further key criteria					
Simplicity in the field	3	3	0	2	2
Applicable without soil test kits	2–3	3	3	3	2–3
Speed of field rating [(b)]	2–3	3	0	3	2–3
Changes with soil depth included?	2	2	1	1	3
Correlation of scores with crop yields					
Field to regional level	2	2	0–1	1–2	2
Large regional to nation level	1–2	1	3	1–2	2
Trans-National	1	0–1	3	0	2

Abbreviations and references: (1) Storie index (Storie, 1933), (2) German BS (German Soil Rating, Rothkegel, 1950), (3) AEZ (Agro-ecological zoning, Fischer et al., 2002), (4) VSA (Visual Soil Assessment, Shepherd, 2000), (5) M-SQR (Muencheberg Soil Quality Rating, Fig. 2, Mueller et al., 2007) (6) SQ (Soil Quality).

[a] Number of indicators/criteria 1, few <5, 2 medium (5–15), 3 high >15.

[b] Time required for field rating (minutes per pedon/unit): 3 fast < 20, 2 medium 20–40, 1 slow >40, 0 no field method.

6. TARGETS AND STEPS TO ASSESSING THE SOIL PRODUCTIVITY FUNCTION IN THE 21ST CENTURY

All approaches for assessing mainly regional-specific and particular aspects of the soil potential for productivity have their eligibility and merits. However, in the resource-limited global world of the 21st century we need more precise instruments for monitoring and controlling the functionality of the soil resource by clearly defined but not only locally valid criteria. A global soil functional assessment and classification framework will enable creation of reliable indicators of farmland quality, consistently over spatial scales, for example a reliable agri-environmental indicator "High quality farmland" which is currently not available. Based on our analysis such a global assessment framework of the soil productivity function has to meet the following requirements:

- a monitoring, controlling and modelling tool of the functional status of the soil resource for crop productivity;
- precise in operation, based on indicators and thresholds of the most functionally relevant parameters identified as soil moisture and temperature regimes, and textural and structural soil attributes;
- consistently applicable over different scales, from a field method to global overviews based on the soil map of the world;
- potential for suitability and capability classifications;
- straightforward for the use in extension and enabling participatory assessments;
- relevant to crop performance, with potential as a crop yield estimator and thus acceptable to farmers and other stakeholders;
- compatible with existing FAO soil classifications and capable of being integrated into new land evaluation frameworks of the 21st century (FAO, 2007).

Both the Canadian Land Suitability Rating System and the Muencheberg Soil Quality Rating meet the majority of these criteria. They contain information on climate and soil properties relevant to crop yield, and soil structure in particular. They have the potential for consistent ratings of the soil productivity function on a global scale but they need to be tested and evolved for this purpose in major agricultural regions. The selection and quantification of indicators and

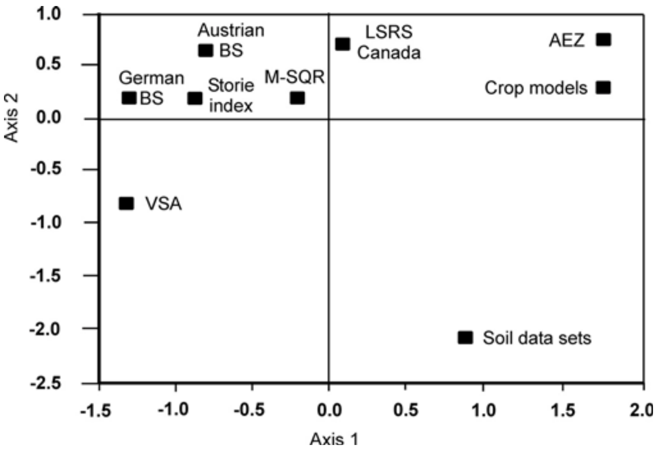


Figure 3. Similarity plot of some soil productivity-relevant evaluation systems. Similarity is expressed by local neighbourhood. Axes are based on computed complex factors and have thus arbitrary meaning. Abbreviations and references: German BS = German Soil Rating (Rothkegel, 1950), Austrian BS = Austrian Soil Rating (Bodenaufnahmesysteme, 2001), Storie index (Storie, 1933), M-SQR (Muencheberg Soil Quality Rating, Fig. 2, Mueller et al., 2007), VSA (Visual Soil Assessment, Shepherd, 2000), LSRS Canada (Land Suitability Rating System, Agronomic Interpretations Working Group, 1995), AEZ (Agro-ecological zoning, Fischer et al., 2002).

definition of thresholds and testing of the accuracy and sensitivity of the overall rating outputs under different environments will be a task of high priority. The latest results of Huber et al. (2008) about identified indicators and thresholds for main threats and degradation risks of soils in the EU will also need to be integrated.

Recent calls and approaches for the standardisation of soil quality attributes and their analyses (Nortcliff, 2002; FAO, 2007; Schindelbeck et al., 2008) will be very important for comparing productivity relevant soil states over the globe. The selection of attributes, data sets and indicators is the basic problem, and needs also to be relevant on a global perspective. Further locally proven and tested approaches and their indicator sets and thresholds (Kundler, 1989; Wienhold et al., 2004; Zhang et al., 2004; Barrios et al., 2006; Ochola et al., 2006; Govaerts et al., 2006; Sparling et al., 2008) referring to typical regions or countries have to be tested on inclusion into the frameworks.

Key indicators are single highly relevant attributes reflecting complex systems. Besides soil structure, soil organic carbon is such a key indicator of soil quality, associated with many soil functions other than productivity. It is also beneficial to agricultural productivity (Kundler, 1989; Rogasik et al., 2001; Lal, 2006; Martin-Rueda et al., 2007; Pan et al., 2009; Jones et al., 2009) at a limited level of inputs of farming but specific targets or thresholds are difficult to specify (Sparling et al., 2003). Despite this difficulty, from a broader perspective of soil functionality, organic carbon must be evolved as a globally key indicator of agricultural soil quality.

7. CONCLUSIONS

(i) There is a lack of a standardised methodology to assess soil productivity potentials for a growing global community of stakeholders achieving a sustainable use of the soil resource. Existing soil and land evaluation and classification systems operate on a regional or national basis. The soil types or reference groups of many existing soil classifications including the latest World Reference Base for Soil Resources are largely based on pedogenic criteria and provide insufficient information on soil functionality. A common internationally applicable method providing field soil productivity ratings is required but does not exist.

(ii) We advocate a straightforward indicator-based soil functional evaluation and classification system supplementing the WRB soil classifications. This could provide a useful tool for monitoring and controlling the soil status for sustainable land use at an internationally comparable scale. It could also serve as a soil productivity estimator providing a fast appraisal of attainable crop yields over different scales.

(iii) This framework has to meet the following criteria: precise in operation, based on indicators and thresholds of soil, consistently applicable over different scales, potential for suitability and capability classifications, adequately crop yield relevant, and capable of being integrated into new land evaluation frameworks of the 21st century.

(iv) Evolving this framework based on favoured methods for this purpose, the Muencheberg Soil Quality Rating (M-SQR) and the Canadian Land Suitability Rating System (LSRS), will be a starting point for assessing sustainable agricultural productivity without compromising soil quality.

Acknowledgements: Authors thank Dr. Eric Lichtfouse and two anonymous reviewers for their helpful suggestions and comments.

REFERENCES

AG Boden (2005) Bodenkundliche Kartieranleitung (KA5), 5th edition, Hannover, 432 p.

Agronomic Interpretations Working Group (1995) Land Suitability Rating System for Agricultural Crops. 1. Spring-seeded small grains, in: Pettapiece W.W. (Ed.), Tech. Bull. 1995-6E, Centre for Land and Biological Resources Research, Agriculture and Agri-Food Canada, Ottawa, 90 p.

Ahrens J.R., Rice T.J., Eswaran H. (2002) Soil Classification: Past and Present, NCSS Newslett. 19, 1–5.

Alcamo J., Dronin N., Endejan M., Golubev G., Kirilenko A. (2007) A new assessment of climate change impacts on food production shortfalls and water availability in Russia, Global Environ. Change 17, 429–444.

Andrews S.S., Karlen D.L., Cambardella C.A. (2004) The Soil Management Assessment Framework: A Quantitative Soil Quality Evaluation Method, Soil Sci. Soc. Am. J. 68, 1945–1962.

Asner G.P., Heidebrecht K.B. (2005) Desertification alters regional ecosystem-climate Inter-actions, Glob. Change Biol. 11, 182–194.

Bacic I.L.Z., Rossiter D.G., Bregt A.K. (2003) The use of land evaluation information by land use planners and decision-makers: a case study in Santa Catarina, Brazil, Soil Use Manage. 19, 12–18.

Baisden W.T. (2006) Agricultural and forest productivity for modelling policy scenarios: evaluating approaches for New Zealand greenhouse gas mitigation, J. Roy. Soc. New Zeal. 36, 1–15.

Ball B.C., Batey T., Munkholm L.J. (2007) Field assessment of soil structural quality - a development of the Peerlkamp test, Soil Use Manage. 23, 329–337.

Barrios E., Delve R.J., Bekunda M., Mowo J., Agunda J., Ramisch J. (2006) Indicators of soil quality: A South–South development of a methodological guide for linking local and technical knowledge, Geoderma 135, 248–259.

Batey T., McKenzie D.C. (2006) Soil compaction: identification directly in the field, Soil Use Manage. 22, 123–131.

BBodSchG (1998) Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Federal Soil Protection Act of 17 March 1998, Federal Law Gazette I, p. 502.

Begon M.R., Townsend R., Harper J.R. (2006) Ecology: from individuals to ecosystems, 4th ed., Blackwell.

Beinroth F.H., Stahr K. (2005) Geschichte und Prinzipien der Bodenklassifikation, in: Blume H.-P., Felix-Henningsen P., Fischer W., Frede H.-G., Guggenberger G., Horn, R., Stahr K. (Eds.), Handbuch der Bodenkunde, Ecomed. 23. Erg. Lfg. 11/05, Section 3.2.1., 22 p.

Bellocchi G., Rivington M., Donatelli M., Matthews K. (2009) Validation of biophysical models: issues and methodologies. A review, Agron. Sustain. Dev. 29, 1–22.

Bibby J.S., Douglas H.A., Thomasson A.J., Robertson J.S. (1991) Land capability classification for agriculture, Macaulay Land Use Research Institute, Aberdeen.

Blum W.E.H. (1993) Soil Protection Concept of the Council of Europe and Integrated Soil Research, in: Eijsackers H.J.P., Hamer T. (Eds.), Integrated Soil and Sediment Research: A basis for Proper Protection, Soil and Environment, Dordrecht: Kluwer Academic Publishers, Vol. 1, pp. 37–47.

Blum W.E.H. (2006) Soil Resources - The basis of human society and the environment, Bodenkultur 57, 197–202.

Bockstaller C., Guichard L., Keichinger O., Girardin P., Galan M.-B., Gaillard G. (2009) Comparison of methods to assess the sustainability of agricultural systems. A review, Agron. Sustain. Dev. 29, 223–235.

Bodenaufnahmesysteme in Österreich (2001) Bodeninformationen für Land-, Forst-, Wasser- und Abfallwirtschaft, Naturschutz-, Landschafts-, Landes- und Raumplanung, Agrarstrukurelle Planung, Bodensanierung und -regeneration sowie Universitäten, Schulen und Bürger. Mitteilungen der Österreichischen Bodenkundlichen Gesellschaft Heft 62, zugleich eine Publikation des Umweltbundesamtes Wien, 2001, 221 p.

Bondeau A., Smith C.M., Zaehle S., Schaphoff S., Lucht W., Cramer W., Gerten D., Lotze-Campen H., Mueller C., Reichstein M., Smith B. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance, Glob. Change Biol. 13, 679–706.

Borlaug N. (2007) Feeding a hungry world, Science 318, 359.

Buol S.W., Sanchez P.A., Cate R.B., Granger M.A. (1975) Soil fertility capability classification: a technical soil classification system for fertility management, in: Bornemisza E., Alvarado A. (Eds.), Soil Management in Tropical America, N.C. State Univ., Raleigh, NC, pp. 126–145.

Bronick C.J., Lal R. (2005) Soil structure and management: a review, Geoderma 124, 3–22.

Brown I., Towers W., Rivington M., Black H.I.J. (2008) The influence of climate change on agricultural land-use potential: adapting and updating the land capability system for Scotland, Climate Research 37, 43–57.

Cannell R.Q., Davies D.B., Mackney D., Pidgeon J.D. (1978) The suitability of soils for sequential direct drilling of combine-harvested crops in Britain: a provisional classification, Outlook Agric. 9, 306–316.

Cassman K.G., Dobermann A., Walters D.T., Yang, H. (2003) Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality, Ann. Rev. Environ. Res. 28, 315–358.

Ceotto E. (2008) Grasslands for bioenergy production. A review, Agron. Sustain. Dev. 28, 47–55.

Ciais P., Reichstein M., Viovy N., Granier A., Ogée J., Allard V., Aubinet M., Buchmann N., Bernhofer C., Carrara A., Chevallier F., De Noblet N.A., Friend D., Friedlingstein P., Grünwald T., Heinesch B., Keronen P., Knohl A., Krinner G., Loustau D., Manca G., Matteucci G., Miglietta F., Ourcival J.M., Papale D., Pilegaard K., Rambal S., Seufert G., Soussana J.F., Sanz M.J., Schulze E.D., Vesala T., Valentini R. (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003, Nature 437, 529–533.

Davis M.L., Masten S.J. (2003) Principles of Environmental Engineering and Science, McGraw-Hill Professional, ISBN 0072921862, 9780072921861, 704 p.

Debaeke P., Aboudrare A. (2004) Adaptation of crop management to water-limited environments, Eur. J. Agron. 21, 433–446.

De la Rosa, D. (2005) Soil quality evaluation and monitoring based on land evaluation, Land Degrad. Dev. 16, 551–559.

De la Rosa D., Anaya-Romero M., Diaz-Pereira E., Heredia R., Shahbazi F. (2009) Soil-specific agro-ecological strategies for sustainable land use – A case study by using MicroLEIS DSS in Sevilla Province (Spain), Land Use Policy 26, 1055–1065.

Del Grosso S.J., Mosier A.R., Parton W.J., Ojima D.S. (2005) DAYCENT model analysis of past and contemporary soil N_2O and net greenhouse gas flux for major crops in the USA, Soil Tillage Res. 83, 9–24.

Duan X.W., Xie Y., Feng Y.J., Yin S.Q. (2009) Study on the Method of Soil Productivity Assessment in Black Soil Region of Northeast China, Agric. Sci. China 8, 472–481.

Durán Zuazo, V.H., Rodríguez Pleguezuelo C.R. (2008) Soil-erosion and runoff prevention by plant covers. A review, Agron. Sustain. Dev. 28, 65–86.

EC (2006) COM 2006/231 2006, Communication from the Commission to the Council, the European Parliament, the European Economic and Sicial Committee and the Committee of the Regions-Thematic Strategy for Soil Protection, Commission of the European Communities, Brussels, 22.9.2006.

Eswaran H., Almaraz R., van den Berg E., Reich P. (1997) An assessment of the soil resources of Africa in relation to productivity, Geoderma 77, 1–18.

FAO (1976) A framework for land evaluation, FAO, Rome, FAO Soils Bull. 32.

FAO (2006) Guidelines for Soil Description (4th ed.), FAO, Rome, 95 p.

FAO (2007) Land evaluation, Towards a revised framework, Land and water discussion paper 6, 107 p.

Farooq M., Wahid A., Kobayashi N., Fujita D., Basra S.M.A. (2009) Plant drought stress: effects, mechanisms and management, Agron. Sustain. Dev. 29, 185–212.

Feller C.L., Thuries L.J.-M., Manlay R.J., Robin P., Frossard E. (2003) "The principles of rational agriculture" by Albrecht Daniel Thaer (1752–1828), An approach to the sustainability of cropping systems at the beginning of the 19th century, J. Plant Nutr. Soil Sci. 166, 687–698.

Fischer G., Sun L. (2001) Model based analysis of future land-use development in China, Agric. Ecosyst. Environ. 85, 163–176.

Fischer G., van Velthuizen H., Shah M., Nachtergaele F. (2002) Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results, International Institute for Applied Systems Analysis, Laxenburg, Austria, 154 p.

Flach K.W. (1986) Modeling of soil productivity and related land classification, in: Siderius W. (Ed.), Land evaluation for land-use planning and conservation in I sloping areas. International Workshop, Enschede, The Netherlands, 17–21 December 1984, Publication 40, International Institute for Land Reclamation and Improvement/ILRI, Wageningen, The Netherlands.

Foley J.A., de Fries R., Asner G.P., Barford C., Bonan G., Carpenter S.R., Chapin F.S., Coe M.T., Daily G.C., Gibbs H.K., Helkowski J.H., Holloway T., Howard E.A., Kucharik C.J., Monfreda C., Patz J.A., Prentice I.C., Ramankutty N., Snyder P.K. (2005) Global consequences of land use, Science 309, 570–574.

Franko U., Oelschlägel B., Schenk S. (1995) Simulation of temperature-, water- and nitrogen dynamics using the model CANDY, Ecol. Model. 81, 213–222.

Gavrilyuk F.Y. (1974) Bonitirovka pochv, Moskva, Vysshaya shkola, 270 p.

Govaerts B., Sayre K.D., Deckers J. (2006) A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico, Soil Tillage Res. 87, 163–174.

Hall R. (2008) Soil Essentials, Managing Your Farm's Primary Asset, Landlinks Press, 1st ed., 192 p.

Hansen S., Jensen H.E., Nielsen N.E., Svendsen H. (1990) DAISY: Soil Plant Atmoshere System Model, NPO Report No. A10, The National Agency for Environmental Protection, Copenhagen, 272 p.

Harrach T. (1982) Ertragsfähigkeit erodierter Böden, Arbeiten der DLG, Bd. 174, Bodenerosion, 84–91.

Hartmann K.-J., Finnern J., Cordsen E. (1999) Bewertung von Bodenfunktionen auf Grundlage der Bodenschätzung, ein Verfahrensvergleich, J. Plant Nutr. Soil Sci. 162, 179–181.

Helming K., Tscherning K., König B., Sieber S., Wiggering H., Kuhlman T., Wascher D., Perez-Soba M., Smeets P., Tabbush P., Dilly O., Hüttl R.F., Bach H. (2008) Ex ante impact assessment of land use change in European regions: the SENSOR approach, in: Helming K., Pérez-Soba M., Tabbush P. (Eds.), Sustainability impact assessment of land use changes, Berlin, Springer, pp. 77–105.

Helms D. (1992) Readings in the History of the Soil Conservation Service, Washington, DC, Soil Conservation Service, pp. 60–73.

Hijmans R.J., Giuking-Lens I.M., van Diepen C.A. (1994) Users guide for the WOFOST 6.0 crop growth simulation model, Technical Document 12, DLO Winand Staring Centre, Wageningen, 145 p.

Hillel D. (2009) The mission of soil science in a changing world, J. Plant Nutr. Soil Sci. 172, 5–9.

Hillel D., Rosenzweig C. (2002) Desertification in relation to climate variability and change, Adv. Agron. 77, 1–38.

Huber S., Prokop G., Arrouays D., Banko G., Bispo A., Jones R.J.A., Kibblewhite M.G., Lexer W., Möller A., Rickson R.J., Shishkov T., Stephens M., Toth G., Van den Akker J.J.H., Varallyay G., Verheijen F.G.A., Jones A.R. (2008) Environmental Assessment of Soil for Monitoring: Volume I, Indicators & Criteria. EUR 23490 EN/1, Office for the Official Publications of the European Communities, Luxembourg, 339 p.

Hulugalle N.R., Weaver T.B., Finlay L.A., Hare J., Entwistle P.C. (2007) Soil properties and crop yields in a dryland Vertisol sown with cotton-based crop rotations, Soil Tillage Res. 93, 356–369.

Jackson L.E., Calderon F.J., Steenwerth K.L., Scow K.M., Rolston D.E. (2003) Responses of soil microbial processes and community structure to tillage events and implications for soil quality, Geoderma 114, 305–317.

Jones A., Stolbovoy V., Rusco E., Gentile A.-R., Gardi C., Marechal B., Montanarella L., (2009) Climate change in Europe. 2. Impact on soil. A review, Agron. Sustain. Dev. 29, 423–432.

Karlen D.L. (2004) Soil quality as an indicator of sustainable tillage practices, Soil Tillage Res. 78, 129–130.

Karlen D.L., Mausbach M.J., Doran J.W., Cline R.G., Harris R.F., Schuman G.E. (1997). Soil quality: a concept, definition and framework for evaluation, Soil Sci. Soc. Am. J. 61, 4–10.

Karmanov I.I., Bulgakov D.S., Karmanova L.A., Putilin E.I. (2002) Modern aspects of the assessment of land quality and soil fertility, Eurasian Soil Sci. 35, 7, 754–760.

Kavdir Y., Smucker A.J.M. (2005) Soil aggregate sequestration of cover crop root and shoot-derived nitrogen, Plant Soil 272, 263–276.

Kay B.D., Hajabbasi M.A., Ying J., Tollenaar M. (2006) Optimum versus non-limiting water contents for root growth, biomass accumulation, gas exchange and the rate of development of maize (*Zea mays* L.), Soil Tillage Res. 88, 42–54.

Kersebaum K.-C. (2007) Modelling nitrogen dynamics in soil–crop systems with HERMES, Nutr. Cycl. Agroecosys. 77, 39–52.

Kersebaum K.-C., Wurbs A., Jong R. de, Campbell C.A., Yang J., Zentner R.P. (2008) Long-term simulation of soil–crop interactions in semiarid southwestern Saskatchewan, Canada, Eur. J. Agron. 29, 1–12.

Keys to Soil Taxonomy (2006) Tenth Edition United States Department of Agriculture, Natural Resources Conservation Service, 333 p.

Klingebiel A.A., Montgomery P.H. (1961) Land capability classification. USDA Agricultural Handbook 210, US Government Printing Office, Washington, DC.

Kopp D., Schwanecke W. (2003) Standörtlich-naturräumliche Grundlagen ökologiegerechter Forstwirtschaft, Kessel Verlag, 2. ed., 262 p.

Kundler P. (1989) Erhöhung der Bodenfruchtbarkeit, VEB Deutscher Landwirtschaftsverlag Berlin, 1st ed., 452 p.

Kurtz D., Schellberg J., Braun M. (2009) Ground and Satellite Based Assessment of Rangeland Management in Sub-Tropical Argentina, Appl. Geogr. 29, in press.

Lal R. (2006) Enhancing crop yield in the developing countries through restoration of soil organic carbon pool in agricultural lands, Land Degrad. Dev. 17, 187–209.

Lal R. (2008) Soils and sustainable agriculture. A review, Agron. Sustain. Dev. 28, 57–64.

Lal R. (2009) Soils and food sufficiency, A review, Agron. Sustain. Dev. 29, 113–133.

Lavalle C., Micale F., Houston T.D., Camia A., Hiederer R., Lazar C., Conte C., Amatulli G., Genovese G. (2009) Climate change in Europe. 3. Impact on agriculture and forestry. A review, Agron. Sustain. Dev. 29, 433–446.

Lichtfouse E., Navarrete M., Debaeke P., Souchère V., Alberola C. (2009) Sustainable Agriculture, Springer, 1st ed., 645 p., ISBN: 978-90-481-2665-1.

Lieth H. (1975) Modeling the primary productivity of the world, in: Lieth H., Whittaker R.H. (Eds.), Primary Productivity of the Biosphere, Springer, Berlin, pp. 237–263.

Lin H., Bouma J., Wilding L.P., Richardson J.L., Kutilek M., Nielsen D.R. (2005) Advances in hydropedology, in: Sparks D.L. (Ed.), Adv. Agron. 85, 2–76.

Louwagie G., Gay S.H., Burrell A. (2009) Addressing soil degradation in EU agriculture: relevant processes, practices and policies, Report on the project 'Sustainable Agriculture and Soil Conservation (SoCo)', JRC Scientific and Technical Reports, ISSN 1018 5593, 209 p.

Lukas V., Neudert L., Kren J. (2009) Mapping of soil conditions in precision agriculture, Acta Agrophys. 13, 393–405.

Lynn I., Manderson A., Page M., Harmsworth G., Eyles G., Douglas G., Mackay A., Newsome P. (2009) Land Use Capability Survey Handbook - a New Zealand handbook for the classification of land, 3rd ed., 164 p.

Martin-Rueda I., Munoz-Guerra L.M., Yunta F., Esteban E., Tenorio J.L., Lucena J.J. (2007) Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf, Soil Tillage Res. 92, 1–9.

Mausel P.W., Carmer S.G., Runge E.C.A. (1975) Soil productivity indexes for Illinois counties and soil associations. Bulletin 752, University of Illinois at Urbana-Champaign, College of Agriculture, Agricultural Experiment Station, 51 p.

McKenzie D.C. (2001) Rapid assessment of soil compaction damage. I. The SOILpak score, a semi-quantitative measure of soil structural form, Aust. J. Soil Res. 39, 117–125.

Medvedev V.V., Bulygin S. Yu, Laktionova T.N., Derevyanko R.G. (2002) Criteria for the Evaluation of Ukrainian Land Suitability for Growing Cereal Crops, Eurasian Soil Sci. 35, 192–202 (Pochvovedenie, 2002, No. 2, 216–227).

Mermut A.R., Eswaran, H. (2001) Some major developments of soil science since the mid-1960s, Geoderma 100, 403–426.

Meyers Lexikon (1925) Bodenbonitierung, Meyers Lexikon, Bibliographisches Institut Leipzig, 7. Auflage, 2. Band, p. 567.

Mirschel, W., Wenkel, K.-O. (2007) Modelling soil-crop interactions with AGROSIM model family, in: Kersebaum K.-C., Hecker J.-M., Mirschel W., Wegehenkel M. (Eds.), Modelling water and nutrient dynamics in soil crop systems: Proceedings of the workshop on "Modelling water and nutrient dynamics in soil-crop systems" held on 14–16 June 2004 in Müncheberg, Germany, Dordrecht Springer, pp. 59–73.

Mueller L., Kay B.D., Hu C., Li Y., Schindler U., Behrendt A., Shepherd T.G., Ball B.C. (2009) Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany: Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals, Soil Tillage Res. 103, 178–187.

Mueller L., Schindler U., Behrendt A., Eulenstein F., Dannowski R. (2007) Das Muencheberger Soil Quality Rating (SQR): ein einfaches Verfahren zur Bewertung der Eignung von Boeden als Farmland, Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 110, 515–516.

Mulengera M.K., Payton R.W. (1999) Modification of the productivity index model, Soil Tillage Res. 52, 11–19.

Munkholm L.J., Schjonning P., Rasmussen K.J., Tanderup K. (2003) Spatial and temporal effects of direct drilling on soil structure in the seedling environment, Soil Tillage Res. 71, 163–173.

Murray W.G., Harris D.G., Miller G.A., Thompson N.S. (1983) Farm appraisal and valuation, Iowa State University Press, 6th ed., 304 p.

Nortcliff S. (2002) Standardisation of soil quality attributes, Agric. Ecosyst. Environ. 88, 161–168.

Ochola W.D., Mwonya R., Mwarasomba L.I., Wambua M.M. (2006) Farm-level Indicators of Sustainable Agriculture, Classification and description of farm recommendation units for extension impact assessment in Koru, Kenya, in: Häni F.J., Pintér L., Herrens H.R. (Eds.), From Common Principles to Common Practice, Proceedings and outputs of the first Symposium of the International Forum on Assessing Sustainability in Agriculture (INFASA), March 16, 2006, Bern, Switzerland, pp. 49–76.

Pan G., Smith P., Weinan Pan W. (2009) The role of soil organic matter in maintaining the productivity and yield stability of cereals in China, Agric. Ecosyst. Environ. 129, 344–348.

Pease J., Coughlin R. (1996) Land Evaluation and Site Assessment: A Guidebook for Rating Agricultural Lands, Second Edition, prepared for the USDA Natural Resources Conservation Service, Soil and Water Conservation Society, Ankeny, IA.

Peerlkamp P.K. (1967) Visual estimation of soil structure, in: de Boodt M., de Leenherr D.E., Frese H., Low A.J., Peerlkamp P.K. (Eds.), West European Methods for Soil Structure Determination, Vol. 2 (11), State Faculty Agricultural Science, Ghent, Belgium, pp. 216–223.

Pehamberger A. (1992) Die Bodenschätzung in Österreich, Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 67, S. 235–240.

Peng L., Zhanbin L., Zhong Z. (2002) An Index System and Method for Soil Productivity Evaluation on the Hillsides in the Loess Plateau, 12th ISCO Conference Beijing 2002, Proceedings, pp. 330–342.

Pierce F.J., Larson W.E., Dowdy R.H., Graham W.A.P. (1983) Productivity of soils: assessing long term changes due to erosion's long term effects, J. Soil Water Conserv. 38, 39–44.

Poluektov R.A., Fintushal S.M., Oparina I.V., Shatskikh D.V., Terleev V.V., Zakharova E.T. (2002) AGROTOOL – A system for crop simulation, Arch. Agron. Soil Sci. 48, 609–635.

Preetz H. (2003) Bewertung von Bodenfunktionen für die praktische Umsetzung des Boden-schutzes (dargestellt am Beispiel eines Untersuchungsgebiets in Sachsen-Anhalt), Ph-D thesis Halle-Wittenberg, 196 p.

Prieto-Blanco A., North P.R.J., Barnsley M.J., Fox N. (2009) Satellite-driven modelling of Net Primary Productivity (NPP): Theoretical analysis, Remote Sens. Environ. 113, 137–147.

Rao N.H., Rogers P.P. (2006) Assessment of agricultural sustainability, Curr. Sci. 91, 43–448.

Reidsma P., Ewert F., Boogaard H., v. Diepen K. (2009) Regional crop modelling in Europe: The impact of climatic conditions and farm characteristics on maize yields, Agric. Syst. 100, 51–60.

Reuter H.I., Kersebaum K.-C., Wendroth O. (2005) Modelling of solar radiation influenced by topographic shading: evaluation and application for precision farming, Phys. Chem. Earth 30, 143–149.

Ritchie J.T., Godwin D.C. (1993) Simulation of Nitrogen Dynamics in the Soil Plant System with the CERES-models, Agrarinformatik 24, 215–230.

Ritter C., Dicke D., Weis M., Oebel H., Piepho H.P., Büchse A., Gerhards R. (2008) An on-farm approach to quantify yield variation and to derive decision rules for site-specific weed management, Precis. Agric. 9, 133–146.

Rogasik J., Schroetter S., Schnug E., Kundler P. (2001) Langzeiteffekte ackerbaulicher Massnahmen auf die Bodenfruchtbarkeit, Arch. Agron. Soil Sci. 47, 3–17.

Roger-Estrade J., Richard G., Caneill J., Boizard H., Coquet Y., De' Fossez P., Manichon H. (2004) Morphological characterisation of soil structure in tilled fields. From a diagnosis method to the modelling of structural changes over time, Soil Tillage Res. 79, 33–49.

Roger-Estrade J., Richard G., Dexter A.R., Boizard H., De Tourdonnet S., Bertrand M., Caneill J. (2009) Integration of soil structure variations with time and space into models for crop management. A review, Agron. Sustain. Dev. 29, 135–142.

Rossiter D.G. (1996) A theoretical framework for land evaluation, Geoderma 72, 165–202.

Rothkegel W. (1950) Geschichtliche Entwicklung der Bodenbonitierungen und Wesen und Bedeutung der deutschen Bodenschätzung, Stuttgart, Ulmer, 147 p.

Rust I. (2006) Aktualisierung der Bodenschätzung unter Berücksichtigung klimatischer Bedingungen, Ph-D Thesis, Göttingen, 281 p.

Sanchez P.A., Couto W., Buol S.W. (1982) The fertility capability soil classification system: Interpretation, application and modification, Geoderma 27, 283–309.

Sanchez P.A., Palm C.A., Buol S.W. (2003) Fertility capability soil classification: a tool to help assess soil quality in the tropics, Geoderma 114, 157–185.

Schellberg J., Hill M., Gerhards R., Rothmund M., Braun M. (2008) Precision agriculture on grassland: applications, perspectives and constraints - a review, Eur. J. Agron. 29, 59–71.

Scherr S.J. (1999) Soil Degradation. A Threat to Developing-Country Food Security by 2020? Food, Agriculture, and the Environment Discussion Paper 27, International Food Policy Research Institute, Washington, DC 20006-1002, USA.

Schindelbeck R.S., van Es H.M., Abawi G.S., Wolfe D.W., Whitlow T.L., Gugino B.K., Idowu O.J., Moebius-Clune B.N. (2008) Comprehensive assessment of soil quality for landscape and urban management, Landsc. Urban Plan. 88, 73–80.

Schroeder D., Lamp J. (1976) Prinzipien der Aufstellung von Bodenklassifikationssystemen, Z. Pflanzenernaehr. Bodenk. 5, 617–630.

Shaxson T.S. (2006) Re-thinking the conservation of carbon, water and soil: a different perspective, Agron. Sustain. Dev. 26, 9–19.

Shepherd T.G. (2000) Visual soil assessment, Volume 1, Field guide for cropping and pastoral grazing on flat to rolling country, Horizons.mw/Landcare Research, Palmerston North, 84 p.

Shepherd T.G. (2009) Visual Soil Assessment. Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country, 2nd ed., Horizons Regional Council, Palmerston North, New Zealand, 118 p.

Smit H.J., Metzger M.J., Ewert F. (2008) Spatial distribution of grassland productivity and land use in Europe, Agric. Syst. 98, 208–219.

Smith P., Martino D., Cai Z., Gwary D., Janzen H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes B., Sirotenko O. (2007) Agriculture, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in: Metz B., Davidson O.R., Bosch P.R., Dave R., Meyer L.A. (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sparling G., Lilburne L., Vojvodić-Vuković M. (2008) Provisional Targets for Soil Quality Indicators in New Zealand, Landcare Research Science Series No. 34, Lincoln, Canterbury, New Zealand.

Sparling G., Parfitt R.L., Hewitt A.E., Schipper L.A. (2003) Three Approaches to Define Desired Soil Organic Matter Contents, J. Environ. Qual. 32, 760–766.

SPSS Inc. (1993) Handbooks SPSS for Windows, Release 6.0, Advanced statistics, 578 p., Professional statistics, 385 p.

Stehfest E., Heistermann M., Priess J.A., Ojima D.S., Alcamo J. (2007) Simulation of global crop production with the ecosystem model DayCent, Ecol. Model. 209, 203–219.

Stenitzer E., Murer E. (2003) Impact of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model, Soil Tillage Res. 73, 43–56.

Storie R.E. (1933) An index for rating the agricultural value of soils, Agricultural Experiment, Station Bulletin 556, University of California Agricultural Experiment Station, Berkley, CA.

Supit I., Hooijer A.A., van Diepen C.A. (1994) EUR 15956 - System description of the WOFOST 6.0 crop simulation model implemented in CGMS (Volume 1: Theory and Algorithms), European Commission, Luxembourg: Office for Official Publications of the European Communities, Agricultural series, Catalogue number: CL-NA-15956-EN-C, 146 p.

Tan G.X., Shibasaki R. (2003) Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration, Ecol. Model. 168, 357–370.

Tang H., van Ranst E., Sys C. (1992) An Approach to Predict Land Production Potential for Irrigated and Rainfed Winter Wheat in Pinan County, China, Soil Technol. 5, 213–224.

Tóth G., Stolbovoy V., Montanarella L. (2007) Institute for Environment and Sustainability, Soil quality and sustainability evaluation, An integrated approach to support soil-related policies of the European Union, A JRC position paper, 40 p.

Tóth T., Pásztor L., Várallyay G., Tóth G. (2007) Overview of soil information and soil protection policies in Hungary, in: Hengl T., Panagos P., Jones A., Tóth G. (Eds.), Status and prospect of soil information in southeastern europe: soil databases, projects and applications, Institute for Environment and Sustainability, 189 p., pp. 77–86.

Van de Steeg J. (2003) Land evaluation for agrarian reform. A case study for Brasil, Landbauforschung Völkenrode, FAL Agricultural Research, Special Issue No. 246, 108 p.

Van Diepen C.A., van Keulen H., Wolf J., Berkhout J.A.A. (1991) Land evaluation: From intuition to quantification, in: Stewart B.A. (Ed.), New York: Springer, Adv. Soil Sci. 15, 139–204.

Verdoodt A., van Ranst E. (2006) Environmental assessment tools for multi-scale land resources information systems. A case study of Rwanda, Agric. Ecosyst. Environ. 114, 170–184.

Verhulst N., Govaerts B., Sayre K.D., Deckers J., François I.M., Dendooven L. (2009) Using NDVI and soil quality analysis to assess influence of agronomic management on within-plot spatial variability and factors limiting production, Plant Soil 317, 41–59.

Walter C., Stützel H. (2009) A new method for assessing the sustainability of land-use systems (I): Identifying the relevant issues, Ecol. Econ. 68, 1275–1287.

Wegehenkel M., Mirschel W., Wenkel K.-O. (2004) Predictions of soil water and crop growth dynamics using the agroecosystem models THESEUS and OPUS, J. Plant Nutr. Soil Sci. 167, 736–744.

Wendroth O., Reuter H.I., Kersebaum K.C. (2003) Predicting yield of barley across a landscape: a state-space modeling approach, J. Hydrol. 272, 250–263.

Wienhold B.J., Andrews S.S., Karlen D.L. (2004) Soil quality: a review of the science and experiences in the USA, Environ. Geochem. Health 26, 89–95.

Wiggering H., Dalchow C., Glemnitz M., Helming K., Mueller K., Schultz A., Stachow U., Zander P. (2006) Indicators for multifunctional land use: linking socio-economic requirements with landscape potentials, Ecol. Ind. 6, 238–249.

Williams J.R., Dyke P.T., Jones C.A. (1983) EPIC – a model for assessing the effects of erosion on soil productivity, in: The Third International Conference on State of the Art Ecological Modelling, Elsevier, Amsterdam, pp. 553–572.

Wong M.T.F., Asseng S. (2006) Determining the causes of spatial and temporal variability of wheat yields at sub-field scale using a new method of upscaling a crop model, Plant Soil 283, 203–215.

WRB (2006) World Reference Base for Soil Resources 2006, A Framework for International Classification, Correlation and Communication, FAO Rome, 2006, World Soil Resources Reports 103, 145 p.

Xiong W., Conway D., Holman I., Lin E. (2008) Evaluation of CERES-Wheat simulation of Wheat Production in China, Agron. J. 100, 1720–1728.

Yakovlev A.S., Loiko P.F., Sazonov N.V., Prokhorov A.N., Sapozhnikov P.M. (2006) Legal Aspects of Soil Conservation and Land Cadaster Works, Eurasian Soil Sci. 39, 693–698.

Zhang B., Zhang Y., Chen D., White R.E., Li Y. (2004) A quantitative evaluation system of soil productivity for intensive agriculture in China, Geoderma 123, 319–331.