The Muencheberg Soil Quality Rating for Assessing the Quality of Global Farmland

Lothar Mueller, Uwe Schindler, T. Graham Shepherd, Bruce C. Ball, Elena Smolentseva, Konstantin Pachikin, Chunsheng Hu, Volker Hennings, Askhad K. Sheudshen, Axel Behrendt, Frank Eulenstein and Ralf Dannowski

L. Mueller (✉) · U. Schindler · A. Behrendt · F. Eulenstein · R. Dannowski
Leibniz-Centre for Agricultural Landscape Research (ZALF) e. V., Eberswalder Str. 84
15374 Muencheberg, Germany
e-mail: mueller@zalf.de

T. G. Shepherd
BioAgriNomics Ltd, 6 Parata Street, Palmerston North 4410, New Zealand
e-mail: gshepherd@BioAgriNomics.com

B. C. Ball
Crop and Soil Systems Research Group, SRUC, West Mains Road, Edinburgh EH9 3JG, UK
e-mail: Bruce.Ball@sruc.ac.uk

E. Smolentseva
Russian Academy of Sciences, Siberian Branch, Institute of Soil Science and Agrochemistry (ISSA), Ac. Lavrentieva avenue, 8, 630090 Novosibirsk, Russian Federation
e-mail: smolentseva@issa.nsc.ru

K. Pachikin
Kazakh Research Institute of Soil Science and Agrochemistry named after U. U. Uspanov, Al Faraby Avenue 75b 050060 Almaty, Kazakhstan
e-mail: kpachikin@yahoo.com

C. Hu
Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, The Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021 Hebei, China
e-mail: cshu@sjziam.ac.cn

V. Hennings
Federal Institute for Geosciences and Natural Resources, Geozentrum Hannover, Stilleweg 2
30655 Hannover, Germany
e-mail: volker.hennings@bgr.de

A. K. Sheudshen
Kuban State Agrarian University, 13 Kalinin Str., 350044 Krasnodar, Russian Federation
e-mail: kubagrohim@mail.ru

L. Mueller et al. (eds.), *Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia*, Environmental Science and Engineering, DOI: 10.1007/978-3-319-01017-5_13,

Abstract Sustainable use of soils is a vital issue in the 21st century to meet global challenges of food security, demands for energy and water, climate change and biodiversity. Eurasia has reasons to tackle and solve these problems soon. It covers the largest landmass and has the highest population density of the earth. Tools for reliable, simple and consistent evaluation of the status of the soil over a wide range of scales can help to assess suitability for crop growth and yield potentials. We explain the Muencheberg Soil Quality Rating (M-SQR) for analysing soil properties that limit crop yields and crop productivity potentials consistently over large regions. The approach is based on 8 Basic Indicators and at least 12 Hazard indicators. Ratings of soil quality are made during normal soil survey mainly by applying visual methods of soil evaluation. A field manual provides rating tables based on response curves and thresholds for different hazard indicators (such as risk of drought). Finally, overall soil quality rating scores ranging from 0 (worst) to 100 (best) characterise crop yield potentials. The current approach is valid for grassland and cropland. Field tests in Eurasia confirmed the practicability and reliability of this approach. We conclude that the Muencheberg SQR has the potential to serve as a global functional reference framework for agricultural soil quality of cropland and grassland. We anticipate the creation of comparable soil functional maps of the whole of Eurasia by the use of this method.

Keywords Soil quality · Indicators · Crop yield · Muencheberg soil quality rating

1 Introduction

The capacity of soil to produce plant biomass is closely related to key global issues of the 21st century like food security (Borlaug 2007), climate change and environmental quality (Lal 2008). This productivity potential of land is dependent on maintaining good soil quality (Karlen et al. 2001). A standardised methodology and framework for assessing agricultural soil quality is likely to be demanded by a growing international community of land users and stakeholders for achieving sustainable high soil productivity. This framework has to meet the following criteria: precise in operation, based on indicators and thresholds of soils, consistently applicable over different scales, potential for use in suitability and land capability classifications, adequately relevant to crop yield potential and capable of being integrated into new land evaluation frameworks of the 21st century (Mueller et al. 2010). In particular, it needs to be relevant to the proposed European Union soil strategy. We start from the hypothesis that the status of the Eurasian soil resource for cropping and grazing could be monitored and controlled by a uniform rating method. This paper aims to explain the multi-indicator-based Muencheberg Soil Quality Rating (M-SQR) and how this was tested in different regions of Eurasia. The magnitude and variability of SQ-Indicators and their underlying data are quantified at a number of agricultural sites across the globe, and correlations of ratings with crop yields are computed and shown.

2 The Muencheberg Soil Quality Rating

The Muencheberg Soil Quality Rating (M-SQR, Mueller et al. 2007a) is based on productivity-relevant indicator scoring which provides a functional rating of soils. The underlying concept is that most terrestrial crops require appropriate seedbed conditions and optimum soil quality for a deep and well-established rooting zone. The M-SQR approach includes both indicators of inherent (soil substrate) and dynamic (soil structure) agricultural soil quality, of topography in terms of slope and of climate in terms of the soil thermal and moisture regimes (Fig. 1).

Two types of indicator have been identified and defined by scoring tables. The first are basic indicators and relate mainly to soil textural and structural properties

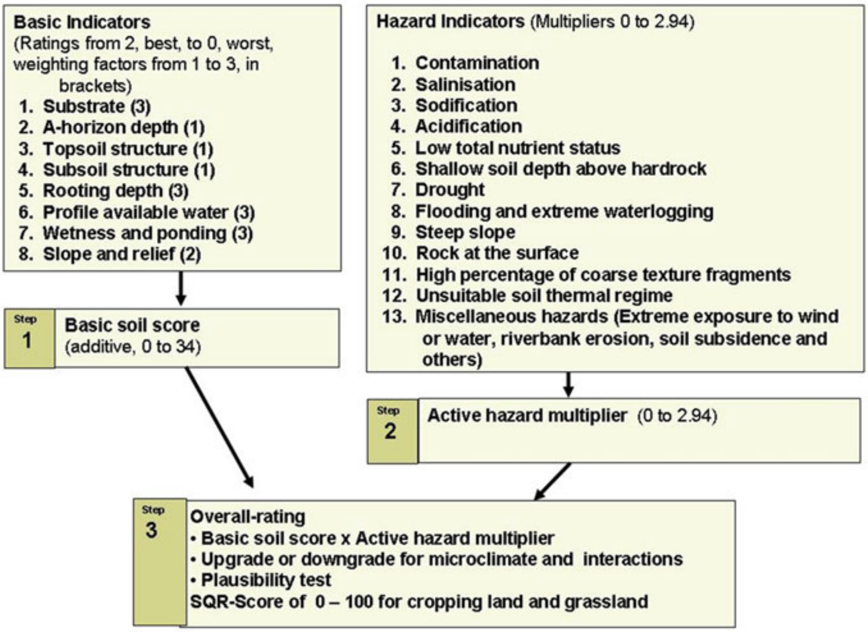

Fig. 1 Rating scheme of M-SQR (Mueller et al. 2007a) First, each of the 8 Basic Indicators is rated on a scale from 2 (best) to 0 (worst), multiplied by a weighting factor from 1 to 3 and then summed. Then the occurrence of Hazard factors is checked and summed as necessary to give a similar rating. The most crop yield limiting Hazard Indicator will be used to estimate a multiplier which may range from 0 to 2.94. The Basic score times the active multiplier will yield an overall M-SQR rating between 0 and 100. Over 100 agricultural research sites worldwide have been rated and classified

relevant to plant growth. These are soil substrate, depth and characteristics of the A horizon, size and shape of topsoil aggregates, features of subsoil structure and compaction, depth of rooting, water supply, wetness and ponding, land slope and relief. These are weighted with extra weight given to rooting and water factors and summed. The second type of indicator is hazard, relating to the most severe restrictions of soil function identified at the site. These are weighted by multipliers according to their relevance. All indicators are rated on a 5-point scale before weighting. The product weighted basic indicator ratings and the most severe (active) hazard indicator provides an overall soil quality rating index (M-SQR score). This M-SQR score may range from 0 (useless for agriculture) to 100 (best soil on a global scale). Indicator ratings are allocated according to a field manual (Mueller et al. 2007b) and utilise soil survey classifications (AG Boden 2005; FAO 2006a), soil structure diagnosis tools and local or regional climate data.

The field procedure for M-SQR consists of digging a small pit to 1 m and augering a hole down to 1.5 m to detect any layering or a shallow watertable. Then the soil profile is scanned to assess the set of indicators shown in Fig. 1 using visual tactile examination, expert-based knowledge and minimum equipment (Fig. 2). A spade, knife and rule are essential for the evaluation of soil textural and

Fig. 2 Essentials for the fieldwork of soil rating. The spade is used for digging the pit and for the spade test of soil structure analysis. The knife is used for checking soil strength and coherence of aggregates. The auger is important for identifying soil texture and other properties like a shallow watertable from 1 to 1.5 m depth. The field manual contains all rating tables. In order to assess the drought risk, monthly data of precipitation and potential evapotranspiration are required. Data can be taken from the local climate estimator New_LocClim 1.10 (FAO 2006b) before starting fieldwork

structural properties. Other instruments like a GPS for marking the exact location and common soil surveying equipment (0.1 n HCL, pH test strips, Munsell colour charts, FAO and/or national guidelines for soil description and others) are useful if the soil has never been surveyed. A basic rating score ranging from 2 (best) to 0 (poorest) will be given for every indicator by the aid of scoring tables related to soil attributes.

The philosophy of the rating procedure is to provide a result based on a minimum of data, but to utilise more detailed information if available. Data need to be allocated to scoring tables, suggested values and sample photographs of the field manual (Mueller et al. 2007b). If for example, analyses of soil density or plant-available water are available and plausible, they should be used instead of the suggested values given in the manual. In the majority of cases, the exact location of the pit for field rating will be clear before field work starts. Where available, use soil and topographic maps, analytical data and other existing information about occurrence of wetness or drought to enhance the reliability of ratings. Monthly climatic data of precipitation and potential evapotranspiration in the main vegetation period are important for assessing the expected drought risk of a site. Some potential evapotranspiration data are inconsistent and unreliable, depending on the method of calculation. Thus, the FAO-Penman–Monteith reference evapotranspiration (Allen et al. 1998) should be used. Climate data of the local climate estimator New Loc_Clim 1.10 (FAO 2006b) are reliable in flat to undulating areas.

The time required for the field rating procedure depends largely on the experience and skills of the expert, but also on the study site and availability of support data. It may range from about 40 min to several minutes. If information about the type of soil is not yet available, it is recommended first to classify the soil by the World Reference Base of Soil Resources (WRB 2006).

3 Important Soil Attributes of the Basic Rating Procedure

The field manual (Mueller et al. 2007b) contains an explanation of indicators, all rating tables, thresholds and orientation guides in detail. Important soil attributes relevant to scoring of Basic indicators are given in Table 1.

On many agricultural sites in temperate climate, this set of attributes and indicators, when summed, is enough to provide productivity-relevant ratings of soil quality at a field scale. The Basic score of M-SQR includes weighting factors which have been developed based on correlations with the crop yield of small grain cereals. The sums of the Basic ratings may range from 0 to 34. They can be converted into a 100-point scale (Upgraded Basic score, UBS) by a multiplier of 2.94. The Upgraded Basic score is often correlated with scores of traditional rating systems, which do not consider drought risk or other hazards.

Table 1 Main soil attributes used for the basic rating

Indicator	Main attributes of scoring	Additional attributes for modifying the score	Relevant depth cm
B1. Soil substrate (WF[a]3)	Soil texture class, parent material	Strong gradients of texture (layering), content of coarse material, low SOM, proportion of artefacts	0–80 (crop land), 0–50 (grassland)
B2. Depth of A- horizon and depth of humic soil (WF1)	Depth of A horizon	Abrupt boundary between topsoil and subsoil, SOM content <4 % (grassland)	0–25
B3. Topsoil structure (WF1)	Type and size of aggregates and pores	Redoximorphic feature	0–25
B4. Subsoil structure (WF1)	Type and size of aggregates and pores, increased soil strength or density	Redoximorphic feature	25–50
B5. Rooting depth and depth of biological activity (WF3)	Occurrence of roots, effective rooting depth	Barriers to rooting and their intensity	150 (cropland), 80 (grassland)
B6. Profile available water (WF3)	Field capacity minus wilting point, rooting depth, capillary supply	Soil texture, stoniness	Rooting zone (<=150)
B7. Wetness and ponding (WF3)	Ponding, depth of ground or perched water table, redoximorphic features, vegetation	Soil position in a depression, wetness due to a perched water table	
B8. Slope and relief (WF2)	Slope at the pedon position	Microrelief and slope aspect at the profile position	

[a] WF = weighting factor of indicator, relevant to crop yield of small grain cereals

4 Important Soil Attributes of the Hazard Rating Procedure

Less fertile regions, widespread worldwide, are characterised by severe restrictions to soil potentials for cropping and grazing. Those hazard factors have the potential to reveal that a soil which looks good with high Basic scores as useless for agriculture. If for example, a fertile Loess soil undergoes severe drought over decades or permanently, no more agricultural cropland use will be possible. There are a number of different potential Hazard factors, but most of them are specific for certain regions. They are combined together into a single index. The reliability of SQ ratings over large regions will be depending on estimating the most critical Hazard factor at the site and its rating. One of the important crop yield limiting factors worldwide is the common site-specific drought risk in the main vegetation period (H7). It may be relevant to almost all regions of the world including humid areas.

The following Table 2 may give an orientation about the relevance of Hazard factors and their recognition.

Hazard indicator ratings are very important for the overall rating result of M-SQR. Having identified the most serious hazard indicator, a multiplier will be derived, which may range from 0 to 2.94. Table 3 gives orientation values of multipliers for drought, which is the factor most limiting soil productivity potentials worldwide. Recommendation values of multipliers consider the number of Hazard indicators with sub-optimum ratings. The number of other hazard factors may also influence the final rating considerably. Additional sub-optimum Hazard indicators like too cool climate (indicator 12) or sodification (indicator 3) are relevant and degrade overall soil quality additionally. If for example, drought is the dominating Hazard indicator at a typical location and has been rated by 1.25 on the basis of the handbook, and additionally Hazard indicators 3 and 12 are also less than 2, the multiplier has to be downgraded to 1.7 using Table 3. To achieve homogenous rating results over larger regions, it is important to estimate the multipliers of drought on the basis of reliable climate data.

The current final rating procedure proposes to check the plausibility of the results and to upgrade or downgrade the result by about 3–15 points, but within the limit of 100 points. Reasons for up- or downgrades are interactions between Hazard indicators, meso- and microclimate and the temporal uniformity of the soil moisture regime within the upper 10 cm.

5 Examples of Field Sites

An example of ratings of four locations in different regions of Eurasia is given in Table 4. Location Muencheberg has sandy soils and the other locations have more favourable Loess soils. Muencheberg and Luancheng are located in moderate climate zones, whilst Ust Kamenka is located in a harsh climate. M-SQR ratings

Table 2 Checklist of Hazard Indicators and criteria for identification (from M-SQR field guide, Mueller et al. 2007b, slightly modified)

Indicator[a]	Thresholds for orientation		
	Direct soil parameters	Indirect parameters of vegetation, climate or others	Reference soil groups (RSG) or qualifiers of WRB (2006)
1. Contamination	Specific for each pollutant according to international thresholds	High risk areas: cities, waste affected soils, vicinity of industrial plants, floodplains	Toxic, (Garbic, Spolic)
2. Salinisation	EC > 4 mS/cm in topsoil	White crusts on soil aggregates or surface, occurrence of halophytes, S-number acc. to Ellenberg >3	Salic, Hypersalic, Puffic, Chloridic
3. Sodification	ESP > 15 % (SAR > 13), pH > 8.2 in topsoil	High pH indicating plants, R-number acc. to Ellenberg of 9	Sodic, Alcalic, Natric
4. Acidification	pH < 5.2 (cropping) or <4.5 (grassland) in topsoil	Low pH indicating plants, R-number acc. to Ellenberg of 3 or lower	Hyperdystric, Hyperthionic
5. Low total nutrient status	Clear deficit of nutrients, cannot be compensated by fertilisation within one year		Hypergypsic, Hypercalcic
6. Soil depth above hard rock	Hardrock or permafrost <120 cm (arable land) or <70 cm (grassland)		Leptic, Lithic, Petric
7. Drought	Water budget in the main vegetation period of 4 month <500 mm, ustic, xeric or aridic soil water regime, total soil water balance in the main vegetation period <50 mm	Climatic water balance in the main vegetation period of 4 months <−100 mm, probability of the occurrence of a dry month >10 %, aridity index acc. to De Martonne <30, benefit of irrigation for cereals	Aridic
8. Flooding and extreme waterlogging	Flooding probability >5 %, peraquic soil water regime	Delay of beginning of farming on cropping land >20d, Grassland mF (Ellenberg) >8, clear benefit of land drainage	Floatic, Gelistagnic, Subaquatic, Tidalic

(continued)

Table 2 (continued)

Indicator[a]	Thresholds for orientation		
	Direct soil parameters	Indirect parameters of vegetation, climate or others	Reference soil groups (RSG) or qualifiers of WRB (2006)
9. Steep slope	Arable land gradient >12 %, grassland gradient >30 %		
10. Rock at the surface	Rock outcrop on arable land >0.01 %, on grassland >0.05 %		Leptosols; Ekranic, Hyperskeletic
11. High percentage of coarse soil texture fragments	Coarse fragments (>2 mm) on arable land >15 % by mass of in topsoil, grassland >30 %		Leptosols; Hyperskeletic, Skeletic
12. Unsuitable soil thermal regime	Cryic or pergelic soil thermal regime, Frigid regime with mean annual temperatures <5 °C	Tundra regions Duration of the frost free period <140 d	Cryosols; Cryic, Glacic

[a] An important characteristic of all indicators is they have rising response curves with crop yields (viz. Higher rating is better). We avoided indicators where response curves have an inner optimum or minimum. For example, if Hazard Indicators 3 (Sodification) and 4 (Acidification) would be combined into an indicator "Soil reaction, pH", the overall rating procedure would work as good as before. However, the approach would lose its potential for the definition of capability classes (for example: Acid soils of moderate productivity potential) as both soils of low and high pH would get low ratings. The functional coding would be not clear without ambiguity

Table 3 Orientation values for ratings and multipliers of hazard indicator 7 « drought»

Rating of drought risk	Orientation value of multiplier for number of H factors, viz. Hazard indicators with values <2[a]			
	0	1	2	3
2 (None)	2.94			
1.75 (None to low)		2.8	2.4	2.1
1.5 (Low)		2.6	2.3	2.0
1.25 (Low to medium)		2.1	1.9	1.7
1 (Medium)		1.8	1.6	1.5
0.75 (Medium to high)		1.5	1.3	1.1
0.5 (High)		1	0.8	0.6

[a] Number of Hazard indicators having ratings <2

consider both aspects. Two rating scores are particularly important. These are the Upgraded Basic score and the overall M-SQR-score. The Upgraded Basic score characterises mainly the physical status of soil for cropping at a certain location. For the locations in Table 4 it reflects the more suitable conditions of Loess soils for plant growth. The overall SQR score considers climate and other factors as specified by Hazard Indicators and that can degrade the soil productivity function seriously. At location Ust Kamenka it is largely determined by unfavourable soil moisture and thermal regimes (Hazard indicators 7 and 12 in Fig. 1). Drought was the dominating

Table 4 Rating examples of four different locations (Smolentseva et al. 2011, modified)

	Muencheberg.D, rainfed	Ust-Kamenka. RU, rainfed	Luancheng.CN, irrigated	Besagasch.KZ, irrigated
Geo-Position[a]	52.7/14.1/37	55.0/83.8/265	37.9/114.7/53	42.8/71.4/620
Climate[b]	540/8.5	514/0.1	537/12.2	330/8,9
Soils[c]	Albeluvisols	Phaeozems	Cambisols	Calcisols
Parent material	Glacial till	Loess	Loess	Loess, re-deposited
Dominant texture class	Sand	Silt loam	Silt loam	Silt loam
Most variable Basic indicators[d]	1,2,5	2, 3	None	5
Upgraded basic score[e]	65 (8)	88 (7)	94 (0)	74
Most limiting H indicator	Drought	Too		
cold+Drought	None	Drought		
Overall M-SQR score[f]	48 (13)	34 (12)	94 (0)	57

[a] Latitude North/Longitude East/Altitude masl

[b] Precipitation in mm/Temperature in °C

[c] Main Reference Soil Group (RSG) of WRB 2006

[d] Basic Indicators 1 = Substrate, 2 = A horizon depth, 3 = Topsoil structure, 4 = Subsoil structure, 5 = Rooting depth, 6 = Profile available water, 7 = Wetness and ponding, 8 = Slope and relief

[e] Basic score in a 100-point scale (100 = best). Mean, (Standard deviation)

[f] 100-point scale: 100 = best for small grain cereals, classes are <20 very poor, 20–40 poor, 40–60 medium, 60–80 good, >80 very good

Table 5 Classes of M-SQR scores and examples of some typical soils

Class of overall soil quality	M-SQR score	Typical examples of soil locations in Eurasia
Very poor	0–20	Soils affected by one or more hazard factors: Solonchaks, Extremely shallow soils, soils at steep slopes, non-irrigated soils in semi-deserts and deserts
Poor	20–40	Loess soils in harsh, too cold and dry climates (cryic or frigid soil temperature regime), soils in Northern Kazakhstan
Moderate	40–60	Sandy and dense loamy soils in temperate subhumid climates of Europe (slight drought risk), loess-like soils in the European part of Russia (frigid temperature regime), some irrigated soils in Central Asia
Good	60–80	Sandy, loamy and clayey soils in temperate humid climates in Central Europe, silty soils in Eastern Europe and Northern China, irrigated soils in Eurasia
Very good	80–100	Loess soils in temperate humid and subhumid climates, in China, Central and Western Europe, irrigated soils in temperate climates

limiting factor of overall soil quality on most sites rated so far. At most locations, the climatic water balance deficit during the main vegetation period could not be compensated by the profile available water. Finally, Luancheng site has a very good overall SQR and crop yield potential, whilst the other three sites have medium or poor conditions for cropping. At local scales, for monitoring and controlling SQR indicators of basic rating like the Upgraded Basic score, the VSA method (Shepherd 2009) or other straightforward evaluation methods of soil structure like VESS (Ball et al. 2007) can be used (Mueller et al. 2012a).

Table 5 gives examples of the classification of soil productivity potentials based on M-SQR scores. It reveals the dominance of the soil thermal and moisture regimes which are largely climate-controlled.

Richter et al. (2009) have shown that these five soil quality classes provide a mapping of agricultural soil quality over larger regions based on available soil and climate data.

6 Overall Rating Scores and Crop Yields

The overall M-SQR score is well correlated with crop yield at a global scale. Figure 3 shows the relationship between M-SQR scores and current yields of small grain cereals at two input levels. The lower linear curve shows crop yields at low and moderate inputs (<100 kg N/ha) and in more ecological farming practices. The regression line is $y = 0.7x$ with a highly significant degree of determination of 0.79. For reasons of readability of this graph, trend lines only are shown. The upper curve is based on high management intensity and high inputs of agro-chemicals (100–450 kg N ha^{-1}). At soils of high and very high quality (M-SQR

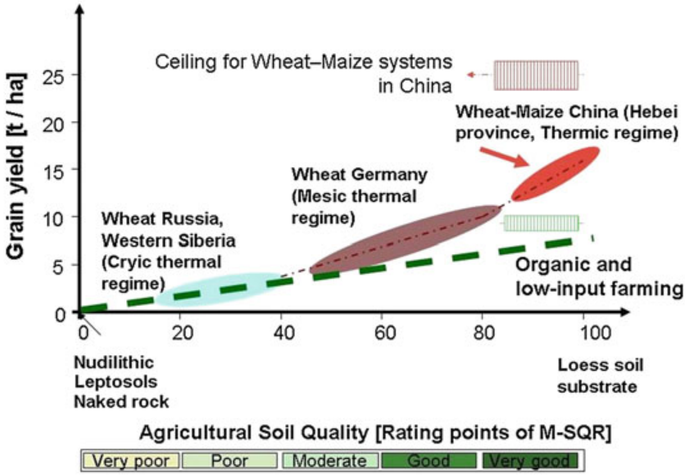

Fig. 3 Agricultural soil quality versus soil productivity (Mueller et al. 2012b, slightly modified). The graph is based on 540 rated soils from different regions of Eurasia. Single points are omitted in this graph. The lower quasi-linear curve is a baseline of M-SQR-Ratings ($y = 0.7x$, $n = 180$, $B = 0.79^{***}$). The upper non-linear curve is also significantly related to yield but reflects high inputs

scores >60) the difference between the curves becomes more marked, showing a high possible response to intensification. Crop yields are higher, the risk of failure is lower and more profit is likely from a given level of inputs.

Crop yields are a measure of productivity and include not only the effects of different soil quality, but also the impact of human activity, skills and management input. At a high level of inputs and management intensity, high crop yields may be achieved even at limited agricultural soil quality, but the risk of resource degradation (mainly water, air and excess fossil energy input) becomes very high. Thus, frameworks for assessing agricultural soil quality are better correlated with crop yields at a low or moderate level of farming intensity.

7 Outlook: Extension of Rating Scales

Currently available evaluation scales of cropland focus on rotations dominated by small grain cereals, reflecting the situation of cropland quality in Central Europe well. However, in some regions other specific crops with different requirements to soil and climate conditions are grown. To cover the majority of cropping and land conditions worldwide, the development of rating scales for other cropping systems is useful and is in progress (Table 6).

Maize and other thermophile grasses like Sorghum are more and more grown in short rotations of Eurasia. Their C-4 metabolism provides high biomass creation in

Table 6 Plant- and management-specific scales of M-SQR

Scale name	Type of dominant land use or crop	Focus of scale	Remark
Grassland scale	Grassland	Grazing for cattle or sheep, pasture, hayland, rangeland	Available
Cropland scale	Small grain cereals dominated rotations	Small grain cereals	Available
Maize scale	Thermophile cereals	Maize or other thermophile cereals, bioenergy crops on cropland	Test phase
Low-input scale	Subsistence cropland agriculture	Inherent soil fertility, organic carbon, zero to low inputs of agrochemicals	In preparation
Multi-cropping scale	Cropland rotations	Limitations of multi-cropping by climate	In preparation

a short growing period at significantly higher water use efficiency as compared to mesophile grasses (Mueller et al. 2005). Increasing temperatures due to climate change promote their extension. A Maize scale is easily created by modification of the thresholds of the Hazard indicator 12 (Soil Thermal Regime).

The usefulness of a Low-input scale is based on the insight that cropping systems worldwide do not follow common rules and conventions about sustainability. Mineral fertilization cannot be provided in many cases of subsistence farming. Under those conditions, the mineral composition of soil and the organic matter content define productivity potential. Creation of a Low-input scale will be also possible in the current framework of M-SQR, but requires some new indicator thresholds and their calibration with crop yields of zero-plots of fertilisation experiments.

The current cropland scale is based on a single cropping approach, which is typical for most areas of cereal-cropping. This could mean a potential overestimation of crop yield potentials on sites having a mesic soil thermal regime as compared to sites having a thermic regime or a mesic regime with mild, frost-free winters. A Multi-cropping scale could be also useful to consider the dominating influence of climate conditions on crop yield potentials.

8 Conclusions

The Muencheberg Soil Quality Rating has potential for assessing the quality of farmland and crop yield potentials on a global scale. More guidance on usage of M-SQR at different scales is needed and can be provided.

It is a realistic goal to create consistent soil functional maps of whole Eurasia by the use of this methodology. These will prove invaluable to land use planners and governments in their strive to improve food security. The Rating can also be used at a smaller scale to help producers get the best from their land.

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