Chapter 26
An Emerging Method of Rating Global Soil Quality and Productivity Potentials

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1 Introduction

Global key issues of the 21st century such as feeding the world population as it grows without control, the scarcity of water and energy, desertification, environmental pollution and loss of biodiversity are raising the pressure on existing and potential agricultural land. Sustainable land use strategies and systems are in

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demand. This requires a reliable characterisation and assessment of soils, their properties and functions on a trans-national scale. One of their key functions is "food and other biomass production" (Blum 1993). This productivity function is related to agricultural soil quality (SQ). A multitude of approaches are available for the quantification of aspects of agricultural SQ. Specific soil and land evaluation schemes already exist for use on a local or national basis. However, their soil data inputs differ; evaluation ratings are not transferable and are not universally applicable to international studies. Babylonian confusion in soil classification terms is preventing international communication and hindering conventions for sustainable soil use and management. There have been some successful efforts to create a framework for the international classification, correlation and communication of soils (WRB 2006, 2014) over the past 15 years. This international classification system, like most national soil classification systems, provides soil names. These names include information about typical processes, features and properties of most soils but do not provide enough information about the overall soil quality and crop yield potentials (Müller et al. 2010). Suitable classification systems should be developed, tested and established. Dokuchaev long ago pointed out the need to classify soils in a way that comprised information about crop yield potentials (In: Dokuchaev 1951).

There are as yet no overall soil quality rating systems that are practicable over different scales, ranging from the field scale to the global scale. The Muencheberg

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Soil Quality Rating (M-SQR, Müller et al. 2007) is intended to close this gap. It shall provide a reliable and simple evaluation of soil quality and crop yield potentials in terms of good, moderate, poor and very poor. Potential applications of the method are soil resource planning, agro-environmental land monitoring, guiding land purchase, and assessing the sustainability and environmental impacts of land use. It is a tool which can be implemented into the next generations of decision support systems (Mirschel et al. 2015) and impact assessment procedures (Helming 2014). The aim of this paper is to give a short description of the Muencheberg Soil Quality Rating, to show the reliability and potential of this approach, and to present updated rating tables for the globally most crop-yield-relevant indicators.

2 The Principle of the Muencheberg Soil Quality Rating

The concept of the M-SQR is that most terrestrial crops require appropriate seedbed conditions and optimum soil quality for a deep and well-established rooting zone. Productivity-relevant indicators (Fig. 1) characterize the quality of this soil zone, and their scoring provides a functional coding of soils. The approach includes indicators of the inherent (soil substrate) and dynamic (soil structure) agricultural soil quality, of the topography in terms of slope and of the climate in terms of the soil thermal and moisture regimes.

Two types of indicator have been identified and defined in scoring tables. The first is Basic Indicators, which relate mainly to the soil's textural and structural properties relevant to plant growth. They are the 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, slope and relief. These are weighted, with extra weight given to rooting and water factors, then the indicators are summed. The Basic Score (ranging from 0–34) or the Upscaled Basic Score (UBS = Basic Score*2.94, maximum score of 100) of M-SQR mainly reflects properties of the texture and structure of soils. Very high Upscaled Basic Scores (>80) are typical for Loess soils or loess-like soil material and medium or low scores (<60) for sandy, stony or waterlogged soils.

The second type of indicators is Hazard Indicators, relating to the most severe restrictions of soil function identified at the site. The most common Hazard Indicators are a lack of water in the main vegetation period (agricultural drought) or drought in combination with an unsuitable temperature regime (soils too cold, too-short vegetation period). The sum of weighted basic indicator ratings and multipliers derived from ratings of the most severe (active) Hazard Indicator yield an overall SQ rating index, i.e. the M-SQR score. If no Hazard Indicators occur, the UBS and M-SQR score are identical. The M-SQR provides a rating of the overall soil quality on a 100-point scale. Loess soils in a temperate climate or under irrigation have the highest overall soil quality (M-SQR scores >80).

Indicator ratings are based on a field manual (Müller et al. 2007) and utilise soil survey classifications (FAO 2006a; WRB 2006), soil structure diagnosis tools and

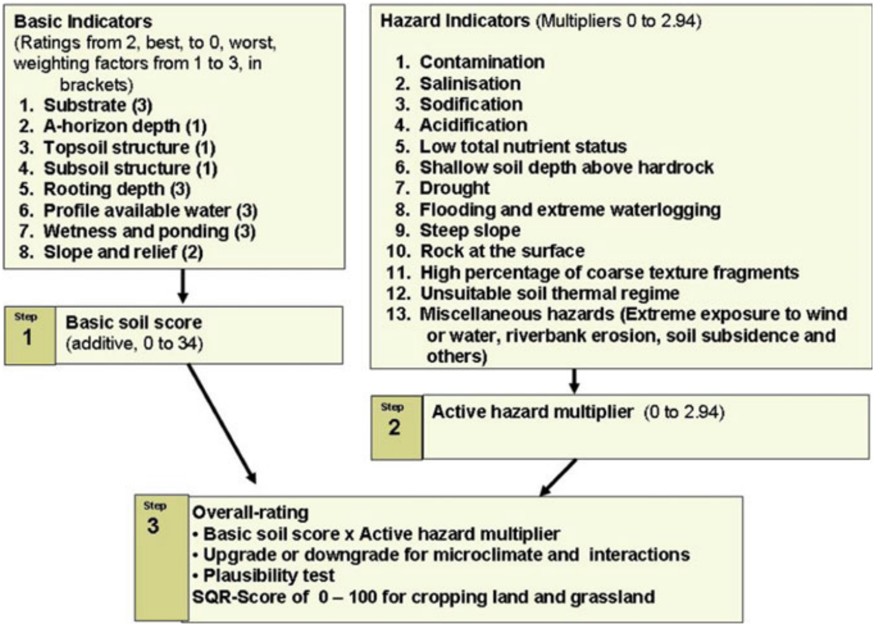

Fig. 1 Rating scheme of M-SQR (Müller et al. 2007). First, each of the 8 Basic Indicators is rated on a scale from 2 (best) to 0 (worst), multiplied by a weighting factor from 1 to 3 and then summed. Then the occurrence of Hazard Factors is checked and summed as necessary to give a similar rating. The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

local or regional soil and climate data. Matching tables provide a fast orientation to commonly used current assessments of individual indicators. These are mainly documented in the FAO Guidelines for soil description (FAO 2006a) the German “Bodenkundliche Kartieranleitung” (AG Boden 2005) and the U.S. National Soil Survey Handbook (USDA/NRCS 2005a).

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 in the field manual (Müller et al. 2007). 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.

Soil quality ratings are restricted to the soil’s suitability for cropping and grazing. The focus is on rainfed cropping in temperate zones and rotations with a dominance of cereals, mainly wheat. A growing number of sample ratings have provided a data basis for the adjustment of individual ratings and the constant improvement of the framework and indicator thresholds.

3 The Field Rating Procedure

The field procedure requires a minimum of equipment. This consists of spade + borer + foot rule + knife + M-SQR field guide (Müller et al. 2007).

Additionally, some equipment can be useful to detect soil properties of particular interest and to document the work. These are:

- A probe for testing the pH (or pH test strips) and electrical conductivity if acidification, sodification or salinisation are expected
- A GPS and camera for geo-referencing and documentation of the visual soil data
- Common soil survey equipment such as the WRB 2006 brochure (WRB 2006), Munsell Colour Charts and 0.1 n HCl if soil rating is being done in combination with a soil taxonomic classification
- A stable plastic box, a larger plastic bag and the field guide “Visual Soil Assessment” (Shepherd 2009) to perform VSA analysis if soil structure restrictions are expected, these being crucial soil quality limiting factors

The field procedure for M-SQR consists of digging a small pit of 0.4–1 m depth and augering a hole down to 1.6 m to detect any layering, a shallow water table or other root-impeding soil properties. A regular soil pit of the kind which is common in soil surveys (Fig. 2) does the job better. It is recommended to perform the M-SQR jointly with a soil taxonomic classification if this is not yet available. The latter gives the soil being studied a name, whilst M-SQR provides quality scores.

The exact sampling point should have been determined using available information from soil maps, airborne data and current or former vegetation patterns. The method requires some experience in soil surveys, such as estimating the soil texture, organic matter content, and soil water balancing and vegetation ecology.

Next, the soil profile is scanned to assess the set of indicators shown in Fig. 1 using visual tactile examination, expert knowledge and minimum equipment.

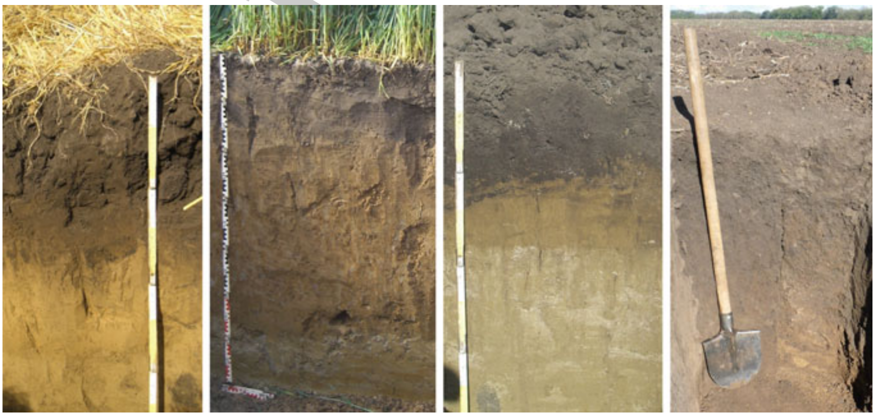

Fig. 2 Examples of soil pits showing different Loess soils that have been classified and rated

A basic rating score ranging from 2 (best) to 0 (poorest) is given for every indicator with the help of scoring tables related to soil attributes (Table 1).

Hazard Indicators in Table 2 are rated in the same way. Not all growth-limiting factors are visible in the soil profile. Only the globally dominating hazard factors of agricultural drought (H7) and unsuitable thermal regime (H12) are controlled by the climate. Monthly data on the temperature, precipitation and potential evapotranspiration are required to assess the soil temperature regime and the drought risk at 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 from the local climate estimator New Loc_Clim 1.10 (FAO 2006b) are reliable in flat to undulating areas.

Table 1 Main soil attributes used for the basic rating (Müller et al. 2014b)

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 organic matter (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

Table 2 Checklist of Hazard Indicators and criteria for identification (Müller et al. 2007, 2014b)

Indicator[a]	Thresholds for orientation		
	Direct soil parameters	Indirect parameters of vegetation, climate or others	Reference soil groups (RSG) or *qualifiers* of WRB 2006, examples
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	Hard rock or permafrost <120 cm (arable land) or <70 cm (grassland)		*Leptic, Lithic, Petric*
7. Drought	Water budget in the main vegetation period of 4 months <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 Cropland >20 d, Grassland mF of Ellenberg >8, clear benefit of land drainage	*Floatic, Gelistagnic, Subaquatic, Tidalic*
9. Steep slope	Arable land gradient >12 %, grassland gradient >30 %		

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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, examples
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 fragments in topsoil, grassland >30 %		Leptosols; *Hyperskeletic, Skeletic*
12. Unsuitable soil thermal regime[2)]	Cryic or pergelic soil thermal regime, Frigid regime with mean annual temperatures <5 °C	Tundra and Taiga regions	Cryosols; *Cryic, Glacic*

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

[b]New orientation values are given in this chapter. They replace the former preliminary values from the field manual (Müller et al. 2007)

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 5 to 40 min.

(a) Krasnoobsk location (Novosibirsk region, Russia), WRB 2006: Haplic Chernozem (Siltic). Very high potential fertility but limitations due to drought in combination with a sub-optimal thermal regime, M-SQR: 42 Rating points, grain yield 3.5 t/ha spring wheat with 70 kg/ha N fertiliser

(b) Haus Duesse location (North Rhine-Westphalia, Germany), WRB 2006: Stagnic Luvisol (Siltic). Temporal wetness in spring, No extreme limitations, M-SQR: 81 Rating points, grain yield 7.5 t/ha winter wheat with 220 kg/ha N fertiliser

(c) Grushevka location (Novosibirsk region, Russia), WRB 2006: Calcic Chernozem (Arenic). Topsoil degraded by wind erosion, extreme limitations by thermal regime and drought, M-SQR: 20 Rating points, grain yield 1.0 t/ha spring wheat without N fertilisation

(d) Krasnodar location (Krasnodar Krai, Russia), WRB 2006: Haplic Chernozem (Pachic, Clayic), minor limitations by drought, M-SQR: 88 Rating points, grain yield 5.2 t/ha winter wheat with moderate N fertilisation, 7.3 t/ha with high fertilisation

4 Rating of Particular Crop-Yield-Limiting Factors (Hazard Indicators)

4.1 *Agricultural Drought (H7)*

Agricultural drought is a complex phenomenon depending mainly on climate and can be influenced by agro-management (drought-resistant varieties, irrigation, soil tillage). We focus on site-specific medium drought intensity, which depends on the climate and soil. In doing so, we assume that there is a correlation between common drought intensity and drought risk. Sites of permanent high drought intensity also face a higher risk of crop failure by drought, e.g. are more unreliable agricultural sites.

Agricultural sites differ in their ability to supply growing plants with water both temporally and spatially. Rating agricultural drought risk aims at characterising spatial differences. The SQR field manual (Müller et al. 2007) proposes some criteria and indexes for their characterisation, such as the soil water budget in the main vegetation period or climatic drought indexes.

Here we propose some updated rating scales of Hazard Indicator H7 (drought risk, Table 3). Two approaches are best suited to characterise the common drought risk of a site. These are (a) the Budget approach, and (b) the Balance approach. They comprise soil and climate properties.

Budget approach: this is based on the assumption that 500 mm of water in the main vegetation period of 4 months provide a very high crop yield of small-grain cereals and other crops. Lower values indicate sub-optimum conditions as shown in Table 3.

The water budget (W_{Bud}) can be calculated as the sum of plant-available water stored in the soil at the beginning of the vegetation period and added to the water supply during the main vegetation period of 4 months, mainly by precipitation, irrigation, and groundwater recharges. The months of May to August can be considered as the main vegetation period in most regions of the Northern hemisphere; in Siberia it is the period of June to September.

$$W_{\mathrm{Bud}} = \mathrm{PAW} + P + \mathrm{Irri} + \mathrm{GWR} \quad (1)$$

where PAW is the plant-available water at the rooting depth, P is the precipitation during the vegetation period, Irri is the irrigation water amount, and GWR is the recharged plant-available groundwater.

PAW is revealed as a product of rooting depth times average plant-available field capacity in this rooting depth. In regions of low winter precipitation where the high potential soil water store (field capacity minus wilting point) is not filled up over the

Table 3 Rating the drought intensity of a pedon or site based on climate and soil parameters over the main vegetation period of 4 months

Score	Drought intensity[a]	Water budget (W_{Bud}), mm[b]	Water balance (W_{Bal}), mm[c]	Precipitation mm	Climatic water balance deficit[d]	De Martonne index[e]	Examples of regions
2	None	>500	>50	>280	<50	>38	Atlantic regions of Denmark, Germany, Netherlands, France etc., irrigated lands in Central Europe and of the North China plain
1.75	Very low	450–500	25–50	250–280	50–110	35–38	Sandy soils in humid regions of Europe, Southern Taiga of Russia
1.5	Low	390–450	−25 to 25	220–250	110–170	32–35	Northeast Germany, Chernozem regions in Europe, Forest steppe of Siberia, Irrigated lands of Central Asia
1.25	Medium	320–390	−100 to −25	180–220	170–230	28–32	Sandy soils in subhumid regions of Europe, Steppes of Siberia
1	High	250–320	−200 to −100	140–180	230–300	24–28	Dry steppes of Russia, Sand-Loess and Loess soils of the Northern plains of the USA and in Inner Mongolia of China
0.75	Very high	180–250	−400 to −200	100–140	300–400	18–24	Dry semiarid regions of the Columbia plateau of the USA, Semi-Deserts of Central Asia
0.5		110–180	–600 to −400	60–100	400–600	13–18	

(continued)

Table 3 (continued)

Score	Drought intensity[a]	Water budget (W_{Bud}), mm[b]	Water balance (W_{Bal}), mm[c]	Precipitation mm	Climatic water balance deficit[d]	De Martonne index[e]	Examples of regions
0.25	Extreme	<110	<−600	<60	>600	<13	Deserts of Central Asia

[a]Scales have been updated and are no longer in accordance with former scales of the M-SQR field guide of 2007 (Müller et al. 2007)
[b]See formula (1), over the main 4 months of the vegetation period
[c]See formula (2), over the main 4 months of the vegetation period, note that this scale is based on ETp data from the local climate estimator New Loc_Clim 1.10 (FAO 2006b)
[d]ETp minus precipitation over the main 4 months of the vegetation period
[e]AI_{DM} = [P/(T + 10) + 12 p/(t + 10)]/2, *P* annual precipitation sum, *T* annual mean temperature, *p* precipitation of the driest month, *t* temperature of the driest month, data are given by the local climate estimator New Loc_Clim 1.10 (FAO 2006b)

winter period, for example on loess soils in a sub-humid or drier climate, the amount of winter precipitation can be considered as the maximum of PAW. GWR can also be an important or dominant source of plant water supply in many soils with a shallow water table (Müller et al. 2005).

The balance approach: the water balance (W_{Bal}) considers the water budget (W_{Bud}) and the potential evapotranspiration (ET_p) in the main vegetation period of 4 months.

$$W_{Bal} = W_{Bud} - ET_p \tag{2}$$

It starts out from the assumption that the water budget has to cover the potential evapotranspiration in the vegetation period to avoid growth limitations caused by drought. No drought risk exists if W_{Bal} is greater than the ET_p during these 4 months. The empirical addition of 50 mm ensures this at a probability of higher than 50 % (Table 3).

Because the establishment of annual crops is based on processes that occur close to the soil surface, and most plant roots are located in this topsoil, solely climate parameters may also serve as indicators of agricultural drought. Examples of updated rating scales for those climate parameters, such as the precipitation and the climatic water balance over the main vegetation period, and the De-Martonne index, are given in Table 3.

All approaches have their advantages and disadvantages. The water budget approach is robust over all regions and should be preferred. The balance approach is more sensitive for Central Europe but may fail in other regions because of unreliable or not specifically adapted ("effective") ETp data. Climate data alone provide only a rough orientation; the climatic water balance deficit may also fail because of unreliable ETp data. We recommend calculating the specific drought intensity values given by all indexes in Table 3 with particular weighting of the water budget approach.

Orientation values for calculating all elements of the water budget and balance are given in soil survey handbooks (AG Boden 2005; FAO 2006a; USDA/NRCS 2005a). Estimating the rooting depth (Basic Indicator 5) is a crucial M-SQR indicator and the most sensitive one. It determines both plant-available water and drought risk assessment. If a field survey does not provide clear information about rooting depth, and soil profiles have a relative homogeneous texture over the depth, data from Table 7 (Appendix) can be applied. Monthly P and ETp data can be taken from the local climate estimator New Loc_Clim 1.10 (FAO 2006b). Orientation data of all components should be dealt with as "effective values", e.g. up- or downgraded due to specific local or regional conditions.

Table 3 also gives some examples of drought for regions where we carried out detailed studies. Most examples refer to "Zonal soils", where soil hydrological processes are dominated by the climate, and not to soils that benefit from shallow water tables or irrigation. The latter soils are characterized by a zero to low drought risk.

4.2 Soil Thermal Regime (H12)

Low temperatures above or in the soil are most important plant-growth-limiting factors in northern latitudes and higher mountain regions. On many Siberian sites, an unsuitable soil thermal regime is the main crop-yield-restricting factor.

Hazard Indicator 12 "Soil thermal regime" is determined by the climate and can be estimated from climate data. Temperatures, mean number of days with positive temperatures (T_{mean} > 0 °C), number of growing days (T_{mean} > 5 °C), and number of days with T_{mean} > 10 °C can help assess and rate the soil thermal regime. The newly introduced Maize scale seems to be useful for Maize and other thermophile

Table 4 Rating of the soil thermal conditions (hazard indicator 12) common cropping scale, rotations dominated by small-grain cereals

Rating of H12, cropland	Annual mean temperature °C	January temperature °C	Days with T_{mean} > 0 °C	Days with T_{mean} > 5 °C	Days with T_{mean} > 10 °C
2 (Suitable thermal regime)	>8	>−4	>290	>220	>170
1.75	6–8	−4 to −8	230–290	190–220	150–170
1.5 (Slightly too cold)	4–6	−8 to −12	210–230	170–190	135–150
1.25	2–4	−12 to −15	200–210	160–170	125–135
1 (Cold)	0–2	−15 to −20	180–200	150–160	110–125
0.75	<0	<−20	160–180	130–150	100–110
0.5 (Very cold)	<0	<−20	<160	<130	<100
0.25	<0	<−20	<140	<100	<60

grasses requiring distinctly higher temperatures in the vegetation period than for common small grain cereals or other grasses of the temperate zone. All data are available from the local climate estimator New Loc_Clim 1.10 (FAO 2006b). Table 4 and Appendix Tables give orientation values of 4–5 relevant criteria. It is unreliable to use only one or two of them for H12 rating. All criteria should be considered with particular weighting of the number of growing days (>5 °C) to get a reliable result.

5 Rules and Updated Orientation Values of the Overall Rating

Having identified the most serious hazard indicator, a multiplier is derived, which may range from 0 to 2.94. The M-SQR field guide (Müller et al. 2007) provides conceptual orientation values for scores of all indicators in Fig. 1. Hazard Rating multipliers given there have broad ranges and may lead to overall scores that still include large subjective variability. Meanwhile, it is possible to confine these intervals if drought (H7) or too-cold climate and soils (H12) are the critical Hazard Indicators.

Practical tests in different regions have shown that it is not only the rating value of the most serious (active) hazard indicators that provides the most plausible results for the multiplier and the overall score. The number and sometimes the rating score of sub-critical hazard indicators are also significant. This holds particularly true for regions outside of Central Europe.

Table 5 gives updated orientation values of multipliers for drought (H7) and unsuitable thermal regime (H12), which are the factors most limiting soil productivity potentials worldwide. Recommendation values of multipliers consider the number of Hazard Indicators with sub-optimum ratings. If, for example, drought is the dominating Hazard Indicator at a typical location and has been rated at 1.25 on the basis of Table 4, and additionally Hazard Indicators 3 and 12 are less than 2, the multiplier has to be downgraded to 1.7 using Table 5.

If other Hazard Indicators than drought (H7) or thermal regime (H12) are critical, this is not yet underpinned by enough data on the soil, crop yield and other factors to give more detailed recommendations for multipliers. Besides conceptual orientation values given in the field manual (Müller et al. 2007), this Table 5 could be used as a preliminary work basis to select a multiplier for calculating the M-SQR score.

Data from Table 5 show that active Hazard Indicator ratings of less than 1 lead to multipliers of also less than 1 in most cases. It is highly probable that those soils will fall into the classes of very low overall soil quality (M-SQR scores <20) or low overall soil quality (M-SQR scores of 20–40).

The 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. The 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.

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Table 5 Orientation values for ratings and multipliers of hazard indicator H7 “drought” and H12 “unsuitable thermal regime” (Universal scale, valid for crops, grassland and Maize if H7 or H12 are the most serious crop-yield-limiting factors)

Rating of indicator H7 or H12	Orientation value of multiplier for number of H factors, viz. Hazard Indicators with values <2[a]				
	0	1	2	3	4
2	2.94				
1.75		2.8	2.5	2.3	2.1
1.5		2.6	2.3	2.1	1.9
1.25		2.3	1.9	1.7	1.4
1		1.9	1.5	1.2	0.9
0.75		1.5	1.2	0.9	0.7
0.5		1.0	0.8	0.5	0.3
0.25		0.5	0.3	0.2	0.1
0		<0.2	<0.1	<0.1	<0.1

[a]Number of Hazard Indicators having ratings <2; note that this scale may provide acceptable results of relative overall scores in the field. However, the application of separate tables given in the Appendix may sometimes correlate better with effective crop and grassland yields and could also be taken into consideration

On the other hand, this Table 5 can be considered as a universal table for estimating multipliers. As long as such tables do not yet exist for other critical Hazard Indicators, this table could serve as a preliminary decision basis for other active Hazard Indicators. It should be noted that these values are better proven than those preliminary ones given in the SQR Manual of 2007 (Müller et al. 2007)

6 Rating Scores and Crop Yields

Following the basic rules of site assessment given by Dokuchaev (1951), the relationships between soil quality and crop yields had to be tested. We dug soil profiles on experimental sites in the main regions of cereal cropping: Europe, Western Siberia and Kazakhstan, Northern China and North America. Profiles were classified according to national keys and the World Reference Base for Soil Resources (WRB 2006). As sites were located on agricultural research stations or experimental fields, crop yield data were provided by research reports. In the case of experimental fields at a practical farm level, we accepted the estimates given by the farm owners or local managers, knowing well that there is a difference between the research station yield level and the practical farm yield level. Data on cereal yield were stratified according to the level of fertiliser input, 0) non-fertilised, (1) low- to medium-fertilised (<100 kg/ha N) and (2) highly fertilised (integrated farming with >100 kg/ha N).

The overall M-SQR score is well correlated with the cereal crop yield over a range of scales. Some data had been given by Smolentseva et al. (2014). Table 6 shows overall regression lines between M-SQR scores on the basis of a dataset enlarged by recent fieldwork from the two last years and other available data from

Table 6 Regression equations of M-SQR rating scores with crop yields

Management category	Regression equation[a]	n	B	SE t/ha
Cropland, unfertilised	$y = 0.048x$	36	0.59*	0.74
Cropland, moderate input (<100 kg/ha of N fertiliser)	$y = 0.072x$	167	0.69*	1.08
Cropland, high input (>100 kg/ha of N fertiliser)	$y = 0.092x$	267	0.65*	2.08
Grassland, unfertilised	$y = 0.07x$	251	0.67*	1.09
Grassland, moderate input (<100 kg/ha of N fertiliser)	$y = 0.085x$	64	0.78*	1.58
Grassland, high input (>100 kg/ha of N fertiliser)	$y = 0.099x$	35	0.80*	2.36

[a]Best linear fit without constant term, Cropland y = grain yield of small-grain cereals in t/ha at 14 % moisture content, x = M-SQR score of cropland scale, Grassland y = Dry matter yield in t/ha, x = M-SQR score of grassland scale
*All regression equations are highly significant at 0.001 %; n number of plots, B (r^2) = degree of estimate, *SE* standard error of estimate

agricultural research stations. This information can be used to check the plausibility of ratings or to estimate yield potentials.

Figure 3 demonstrates that M-SQR ratings reflect the crop yield potentials of grassland ecosystems well. This figure shows also that the yield gap between yield potentials and current yields is significant due to poor grassland management. Grassland degradation is a great threat to the ecosystems of Central Asia and to other dry regions. It seriously affects global biological cycles and desertification. Tendencies to desertification have become significant for the Steppe regions of Siberia (Schreiner and Meyer 2014). Recovering ecosystem functions by proper

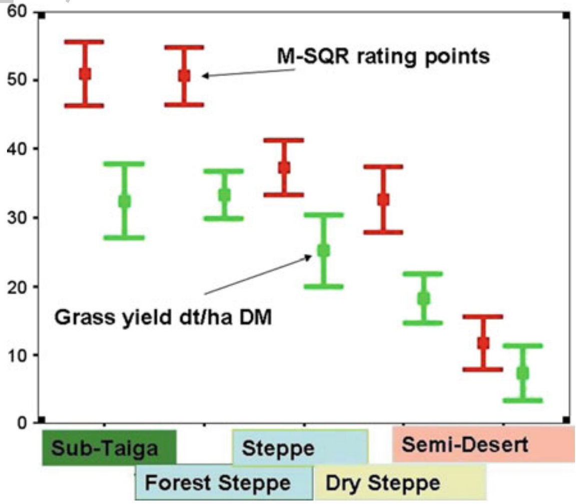

Fig. 3 Grassland rating scores and effective grassland yield (EGY) of different soil ecological zones of Russia and Kazakhstan. EGY is the annual above-ground biomass minus non-palatable plants in decitonnes of dry matter per hectare

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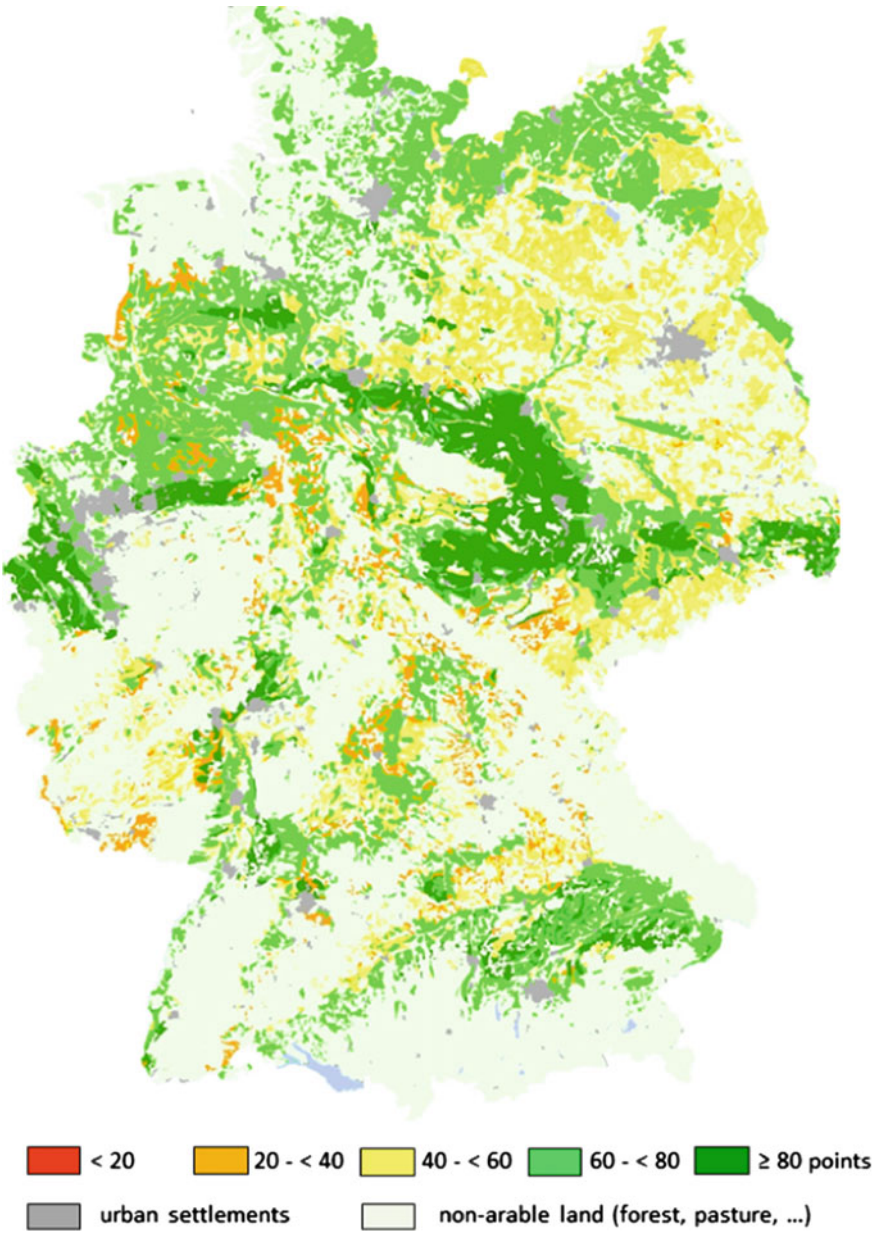

Fig. 4 Draft of the German soil quality map of cropland based on M-SQR (Richter et al. 2009). It shows five soil quality classes, providing a mapping of agricultural soil quality over larger regions based on available soil and climate data. Meanwhile, the German Federal Institute for Geosciences and Natural Resources (BGR) in Hannover has developed slightly modified maps (Hennings et al. 2015). Users interested in the underlying database may get more information from the homepage of the BGR (BGR 2014)

management and others based on a comprehensive grassland basic inventory and monitoring including M-SQR would be a decisive step towards sustainability in handling land resources (Müller et al. 2014c).

7 The Potential of M-SQR for Creating Soil Quality Maps

One of the aims of the M-SQR framework is to provide soil quality and productivity potential assessments consistently over different spatial scales. When this approach was developed, the prime focus was on making the field procedure operable as a basis for monitoring and soil and water management at the field or regional scale. More and more focus could be put on the cross-regional (Helbig, In: Müller et al. 2013), national (Richter et al. 2009; BGR 2014, Fig. 4) and trans-national scale when it was shown that it is not necessary to start new high-resolution soil surveys to map M-SQR data. Available soil categories and databases or existing national soil rating maps can be utilised based on correlations (Müller et al. 2011b) or parameterizations of mapping categories. This is particularly easy to install for countries which already have sophisticated soil information systems, such as Germany or the USA. In Germany, for example, scores of M-SQR are significantly correlated with scores of the official traditional soil rating system (“Ackerzahl” of the “Bodenschätzung”, Müller et al. 2011b; Hennings et al. 2015). Those data, or soil series data from the US Soil Conservation Service (USDA/NRCS 2005a, b), provide the best preconditions for creating soil quality maps at field and regional scales, which will have high conformity with small-scale cross-regional data.

The same could be done for the agricultural lands of Russia, beginning with small-scale mapping. Fieldwork has shown that soil types and texture classes of the Russian soil taxonomy are associated with typical ranges of Basic and Hazard Indicators of the M-SQR system. All data are available in databases of Russian soil information systems (Stolbovoi and Fischer 1997; Afonin et al. 2008; Mikheeva 2013) and climate databases (FA0 2006b).

8 Conclusions

- A classification of soils by WRB (2006, 2014) in combination with M-SQR provides sufficient information about soil properties, processes and productivity potentials.
- Soil quality scores characterise productivity potentials of sites at a defined level of inputs.
- Drought (lack of plant-available water in the vegetation period) and an insufficient thermal regime are the most crop-yield-limiting factors worldwide.

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- We developed rating tables to evaluate these and other factors related to the productivity potentials of cropland and grassland.
- The Muencheberg Soil Quality Rating is practicable and reliable. It has the potential to be applied as a global soil quality reference system both in the field and for mapping purposes.
- This rating system has the potential to be included in the monitoring, decision support, impact assessment and management systems of Eurasian grassland and cropland ecosystems. These are important for halting land degradation and initiating sustainable land use.
- As a first concrete step, our available data and knowledge would allow us to create a crop yield potential map of Russia and neighbouring countries using the M-SQR methodology.

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Appendix: Further Updated Rating Tables

See Tables 7, 8, 9, 10, 11 and 12

Table 7 Potential rooting depths[a] of homogeneous mineral soils of deep ground water table

Coarse sand and coarse material (>0.63 mm, g/100 g)	Clay and silt content (<0.063 mm, g/100 g)				
	0	15	30	60	>60
0	0.70 (0.75)	0.90 (1)	1.05 (1)	1.30 (1.5)	1.50 (2)
20	0.45 (0.25)	0.65 (0.5)	0.85 (0.75)	1.05 (1.25)	1.25 (1.5)
30	0.35 (0)	0.55 (0.25)	0.75 (0.75)	0.95 (1)	1.10 (1.25)
40	0.30 (0)	0.45 (0.25)	0.60 (0.5)	0.85 (0.75)	0.95 (1)
60	0.30 (0)	0.30 (0)	0.40 (0)	0.60 (0.5)	0.75 (0.75)
>60	0.30 (0)	0.30 (0)	0.30 (0)	0.30 (0)	0.40 (0)

[a]The first number is the rooting depth in meters, the second number in parentheses is the rating score for Basic Indicator 5 (Rooting depth, 0 = Minimum, 2 = Maximum), clay and silt content are related to the soil texture fraction <2 mm, coarse sand and coarse material are related to the overall mass of the soil

Table 8 Orientation values for ratings and multipliers of Hazard Indicator 7 (drought), cropland

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

[a]Number of Hazard Indicators having ratings <2

Table 9 Rating of the hazard indicator 12 (soil thermal conditions), scale for grassland

Rating of H12 for grassland	Annual mean temperature (°C)	Mean temperature in January (°C)	Days with T_{mean} > 0 °C	Days with T_{mean} > 5 °C	Days with T_{mean} > 10 °C
2 (suitable thermal regime)	>8	>−4	>280	>220	>170
1.75	6–8	−4 to −8	230–280	190–220	150–170
1.5 (slightly too cold)	4–6	−8 to −12	210–230	170–190	135–150
1.25	2–4	–12 to −15	195–210	160–170	125–135
1 (cold)	0–2	−15 to −20	170–195	150–160	105–125
0.75	0 to −5	−20 to −25	140–170	120–150	80–105
0.5 (very cold)	−5 to −10	<−25	120–140	60–120	35–80
0.25	<−10	<−25	<120	<60	<35

Table 10 Rating of the hazard indicator 12 (soil thermal conditions), scale for maize cropping

Rating of H12 for Maize	Annual mean temperature (°C)	Mean temperature in July (°C)	Days with T_{mean} > 5 °C	Days with T_{mean} > 10 °C
2 (Suitable thermal regime)	>10	>20	>230	>200
1.5 (Slightly too cold)	8–10	18–20	220–230	160–200
1 (Cold)	6–8	16–18	200–220	120–160
0.5 (Very cold)	0–6	14–16	140–200	80–120
0	<0	<14	<140	<80

Note that this scale is designed to assess restrictions for maize biomass; it does not distinguish between the potentials of maize for corn from maize for silage. A rule of thumb is that maize for corn requires about 150 days with temperatures >10 °C

Table 11 Orientation values for multipliers of hazard indicator 12 (unsuitable thermal regime), scale for cropland

Rating of indicator H12 for cropland	Orientation value of multiplier for number of H factors, viz. Hazard indicators with values <2[a)]				
	0	1	2	3	4 or more
2	2.94				
1.75		2.8	2.3	2.1	2
1.5		2.7	2.2	2.0	1.7
1.25		2.3	1.9	1.7	1.3
1		2	1.4	1	0.8
0.75		1.5	1	0.7	0.5
0.5		1	0.7	0.5	0.4

[a]Number of Hazard Indicators having ratings <2

Table 12 Orientation values for multipliers of hazard indicator 12 (unsuitable thermal regime), scale for grassland

Rating of indicator H12 for grassland	Orientation value of multiplier for number of H factors, viz. Hazard Indicators with values <2[a]				
	0	1	2	3	4 or more
2	2.94				
1.75		2.8	2.6	2.3	2
1.5		2.7	2.4	2.1	1.7
1.25		2.4	2.1	1.8	1.4
1		2.1	1.7	1.5	1.1
0.75		1.7	1.4	1.1	0.7
0.5		1.4	1	0.7	0.4

[a]Number of hazard indicators having ratings <2

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