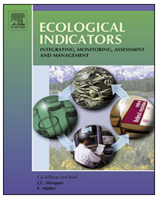
Ecological Indicators 94 (2018) 151–169

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

# Soil quality indicators – From soil functions to ecosystem services

Thomas Drobnik[a,*], Lucie Greiner[b], Armin Keller[b], Adrienne Grêt-Regamey[a]

[a] *Planning of Landscape and Urban Systems PLUS, Swiss Federal Institute of Technology (ETH), Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland*
[b] *Agroscope Reckenholz-Tänikon ART, Reckenholzstrasse 191, 8046 Zurich, Switzerland*

ARTICLE INFO

*Keywords:*
Soil quality index
Ecosystem services
Spatial decision-making
Trade-off assessment

ABSTRACT

Soils provide a broad set of vital ecosystem services (ES), yet soils are under threat worldwide. To avoid further degradation of soils and, in consequence, provision of soil-based ES, soil science has been calling for a comprehensive consideration of soil quality in decision-making, as soils are marginalized as a mere surface. Although a myriad of soil quality indicators exist, their disciplinary focus complicates discussion of conflicting soil uses. We present a novel approach to base soil quality not on soil function assessment alone but on a soil's ability to support various ES. The soil quality index SQUID (**S**oil **QU**ality **I**n**D**icator) links a set of ten different soil functions to various ESs using an expert-based Delphi approach. We apply it to ten suburban municipalities in the Canton of Zurich, Switzerland, where fast development of urban structures has led to significant loss of fertile soils over the last two decades. To estimate the potential and the problems of the SQUID index, we compare it to an established soil quality index designed for spatial planning (BOKS – soil concept Stuttgart). Results suggest that SQUID is at a disadvantage for general overviews, but can be highly useful when detailed trade-off assessments are required. We conclude that the SQUID index might be a promising approach to better integrate soil quality into decision-making, as it has the potential to overcome disciplinary boundaries and to foster trade-off discussions between different, possibly conflicting soil use interests.

## 1. Introduction

Soils are under threat worldwide (FAO and ITPS, 2015; Stolte et al., 2016; Tóth et al., 2008). Intensification and competing uses of soils for cropping, forestry, pasture, and urbanization are increasingly impacting the provision of life-supporting services such as food production, clean water for drinking, flood mitigation, and habitat for plants and animals. While soil scientists have increasingly called for a comprehensive consideration of soils and their services in decision-making (Doran, 2002; Doran and Parkin, 1994; Herrick, 2000; McBratney et al., 2014), soil is usually omitted from land use decisions and is marginalized as a two-dimensional surface whose multitude of functions is not explicitly recognized (Koch et al., 2013). In the United Nations Environment Programme (UNEP) report on Green Economy (UNEP, 2011), soil is not explicitly but implicitly mentioned as part of the natural capital. The final report from the Commission on Sustainable Agriculture and Climate Change (CGIAR report; Beddington et al. (2012)) lists several key recommendations for achieving better food security, but none of them includes soil. The recently published United Nations Sustainable Development Goals follow along the same lines, with soil being mentioned only once explicitly across a total of 17 goals and numerous formulated targets (in goal 15: "life on land") (United Nations, 2015).

Moreover, soil science itself is "atomized", as Bouma (2010) calls it: relevant soil information is fragmented across many isolated, highly specialized subdisciplines, limiting its usefulness outside the disciplinary scope. Janzen et al. (2011) even goes as far as to imply that people not directly involved with soil basically do not perceive it at all. In addition, soil classification data, interpretation, and structure of available soil information is often complex and hard to understand for anybody outside the soil science community (Bouma, 2014). Soil scientists are aware of these problems and have developed various concepts to improve communication and cooperation both within as well as across disciplines, and to increase interaction with stakeholders (Bouma, 2010, 2014; Bouma et al., 2012; Bouma and McBratney, 2013; Janzen et al., 2011; Koch et al., 2013; McBratney et al., 2014). The concept of soil functions (Blum, 2005) defines six tasks a soil fulfils, including biomass production, protection of humans and the environment, gene reservoir, physical basis of human activities, source of raw materials, and geogenic and cultural heritage. In 2006, a seventh aspect was added by the European Commission, emphasizing the ability of soil to act as a carbon pool (CEC, 2006). Soil functions are closely related to soil quality (Doran and Parkin, 1994; Karlen et al., 2003; Kibblewhite et al., 2008), which was defined by an working group of the American Soil Science Society as "the capacity of specific kind of soil to function

---

* Corresponding author.
*E-mail addresses:* drobnikt@ethz.ch (T. Drobnik), lucie.greiner@agroscope.admin.ch (L. Greiner), armin.keller@agroscope.admin.ch (A. Keller), gret@ethz.ch (A. Grêt-Regamey).

https://doi.org/10.1016/j.ecolind.2018.06.052
Received 26 June 2017; Received in revised form 19 June 2018; Accepted 22 June 2018

within natural or managed ecosystem boundaries…" (Karlen et al., 1997). The concept of assessing soil functions emphasize the multifunctionality of soils. More recently, the ecosystem service (ES) concept has been considered a challenging yet promising approach for fostering the communication of nature's capital (MEA, 2005). Several authors have used it to link soil functions and benefits for human well-being (Adhikari and Hartemink, 2016; Breure et al., 2012; Dominati et al., 2010), and Greiner et al. (2017) show that the capacity of soils to deliver ES is largely determined by the soil functions.

There exist many frameworks for soil quality assessments and evaluations, with various forms of aggregation and indicators. Although the frameworks share the aim of providing a comprehensive description of soil quality, they can broadly be divided into two groups with regard to their main focus: (1) Indicator frameworks that describe the current state of the soil system, by assessing agricultural soil quality based on detailed field measurements (Arshad and Martin, 2002), by analyzing statistically soil data bases to infer which soil properties and soil functions are most important for a high-quality soil (Shukla et al., 2006), or by elaborating on the status of specific soil threats (Desaules et al., 2010). (2) Indicator frameworks that focus on soil quality change and applied soil management: They discuss the productivity of soils under different management systems (Oberholzer et al., 2012), compare farming systems (Fließbach et al., 2007), or discuss in detail the advantages of soil biota as a soil quality indicator (Schloter et al., 2003). More examples for soil quality indicators belonging to one of those two groups can be found in Bastida et al. (2008). Many of the proposals for soil quality indicators focus on land management in the context of a singular discipline such as agriculture (Arshad and Martin, 2002; de Paul Obade and Lal, 2016; Oberholzer et al., 2012) or soil pollution (Desaules et al., 2010). Other indicators provide specialized information for other soil experts (Fließbach et al., 2007; Schloter et al., 2003). Finally, there are also indicators that are designed from a purely scientific point of view and lack meaning for non-scientists (Robertson and Hull, 2001).

Soil quality frameworks designed for spatial planning are rare, though. Wolff (2006) developed and operationalized a concept for taking soil quality into account in spatial planning in the greater region of Stuttgart, Germany. Another concept was developed for Austria by Knoll et al. (2010) and Haslmayr et al. (2016). Both concepts focus entirely on the containment of settlement expansion and the associated infrastructure. Wolff (2006) aggregates soil quality in terms of points (higher = better soil) based on natural soil functions (i.e., suitability for agriculture and plants, water retention, filter for pollutants) and anthropogenous soil degradation (i.e., by landfills) and budgets the availability of soil quality points for municipalities for new urban areas. Haslmayr et al. (2016) also assess various soil functions (i.e., habitat for organisms, potential as a habitat for natural plant communities, natural fruitfulness of the soil, and more) to determine overall soil quality, which is then implemented as "spatial resistance" for developing a site. The "spatial resistance" of a soil depends on the highest performance of its assessed soil functions, with higher performance translating into higher resistance. In case an area achieves the maximum score for spatial resistance, it is treated as soil preservation area where anthropogenic development requires compensation measures. While both of these soil indicators are highly aggregated and work well in top-down planning environments (i.e., defining and setting planning goals at the highest hierarchy level without considering feedback from lower hierarchy levels), it has been shown that aggregated indicators are less effective when scale-sensitive trade-off assessments and impact evaluations are needed (Drobnik et al., 2016; Geneletti, 2011; Gret-Regamey et al., 2014). This is especially true for soil, and Bouma (2010) explicitly advises against a single aggregated indicator as a solution if soil quality is meant to be implemented in a meaningful way into decision-making. For Letey et al. (2003) a single soil quality index even is "prohibitive". Terribile et al. (2015) provide further evidence that soil-related decision-making requires not a single soil quality indicator but several: they present and discuss a comprehensive spatial planning tool with soil fully integrated into various models and decision-support modules. While it is a promising tool for their specific case study region, they also point out that both the decision-support tool and the results lack any transferability to other regions.

This paper adds to the existing literature on soil quality indices, but follows the call of Breure et al. (2012) and Bouma (2014): it focuses on how to link soil functions and ES, and whether an ES-based soil quality index can provide a useful information for steering spatial development. We compare two soil-quality indices designed for spatial decision-making: (1) the "Bodenkonzept Stuttgart" (BOKS) soil quality index established by Wolff (2006), and (2) a new soil quality index focusing on soil-supported ES provision named SQUID (**S**oil **QU**ality **I**n**D**icator). Rather than relying on a direct aggregation of various soil functions to form an index, SQUID focuses on the diversity of ES as well as the dependence of each of these services on different soil functions using expert assessments. Both soil quality indices are based on high-resolution soil functional assessments (Mueller et al., 2007; Viscarra Rossel et al., 2006). We begin with a presentation of the different soil functions used for creating the indices before we introduce the indices themselves. In a next step, soil quality maps for a case study area in Switzerland are generated based on the indices, and the outcomes are analyzed and compared. We conclude with discussing the strengths, weaknesses and possibilities of the two indices, specifically with respect to their application in steering spatial development.

## 2. Case study area

Our case study is located in the Swiss Central Plateau, within the Canton of Zurich in the northeast of Switzerland. It consists of the ten municipalities Oetwil am See, Fehraltorf, Illnau-Effretikon, Bubikon, Gossau, Grueningen, Egg, Moenchaltorf, Uster, and Volketswil. The biggest municipality in the case study region is Uster with 33.853 inhabitants and an average population growth rate of 1.3% over the last 15 years (ZSO, 2016). The whole case study region covers an area of 15.188 ha, 2336 (15.4%) of which are considered settlement area, and 7914 ha (52.1%) are agricultural land. The remaining areas are split up between forest (22.1%), waterbodies (0.5%), infrastructure (6.1%), and unproductive areas (3.4%) (ZSO, 2016). The municipalities are located within the metropolitan region of Zurich and are well connected to Zurich with respect to both public as well as private transportation means. With respect to soil, the majority of the northern case study area (municipalities A to D in Fig. 1) is covered by fertile, deep soils with good water cycle regulation that can be used for any kind of agriculture. In contrast, soils in the southern part of the case study area are susceptible to waterlogging and often shallow, leading to grassland-oriented agriculture (Kanton Zurich, 2012).

## 3. Methods

### 3.1. Soil functions and soil-based ecosystem services

### 3.1.1. Assessment of soil functions

Basis for this study are soil function assessment (SFA) maps originating from the work of Nussbaum et al. (2017) and Greiner et al. (2017). The SFA maps used for this study cover 8183 ha of the case study area, but do not include forests, water bodies, small gardens within settlement areas, and sealed surfaces. They are point maps with a resolution of 20 × 20 m, where each point provides information on the quality of 10 different soil functions. The quality of these soil functions is given as degree of fulfillment, i.e. how well does a soil perform with respect to a given function, ranging from 1 (very low) to 5 (very high) (Greiner et al., 2017; Greiner et al., in review). For creation of the SFA maps, a range of methods was applied (Table 1 provides a comprehensive overview), combining both measured and derived information on soil parameters into an ordinal scaled score. *Water cycling*