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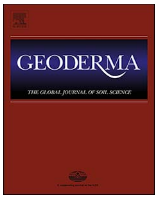

A new look at soil phenoforms – Definition, identification, mapping

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ABSTRACT

The soil *genoform* vs. soil *phenoform* distinction was suggested twenty years ago by Droogers and Bouma to recognize management-induced differences among pedons with the same long-term pedogenesis and included in the same soil map unit, these changes being sufficient to cause important and persistent differences in soil functions. To support the recent increased interest in soil change and soil health, we propose conceptual and operational definitions of soil genoforms and soil phenoforms, and suggest techniques to identify and map them. We define soil genoforms as soil classes as identified by the soil classification system used as the basis for detailed soil mapping in a given area. This avoids the difficulty of defining when human intervention has been sufficient to create new genoforms – by definition this is when new lowest-level classes are recognized in the classification system, based on diagnostic horizons and properties. We then define soil phenoforms as persistent variants of a genoform with sufficient physical or chemical differences to substantially affect soil functions. Soil phenoforms must be persistent enough that substantial management interventions are necessary to change them, thus seasonal and rotational variants are excluded from the concept. Soil phenoforms can be identified by measurements of indicator soil properties at locations within a soil genoform with different management and investigating if these are different enough to affect soil functions, notably soil hydrology and crop yield. Digital mapping of soil phenoforms will likely use maps of current and historical management as predictors. In areas with intensive or changed management, mapping should be repeated every few years to identify areas of changed soil phenoforms and new genoforms.

1. Introduction

Soils are the result of pedogenesis controlled by soil forming factors, as well-summarized conceptually by Jenny (1941, 1980) and successors. Soil mappers attempt to identify geographically-compact areas with a narrow range of soil forming factors which they then delineate at large to medium scales as more or less homogeneous polygons and name at the lowest level of a soil classification system, e.g., soil series within (USA) Soil Taxonomy (Soil Survey Division Staff, 1999) or fully qualified World Reference Base (WRB) names (FAO, 2014). Digital soil mapping (DSM) does the same but on a grid cell basis (McBratney et al., 2003): each cell is classified with the name of the dominant soil class, and in addition information may be given about other classes present in the cell and their relative proportions, or the probability of occurrence of each class (Hengl et al., 2017). These map units or sets of grid cells are considered to have more or less the same pedogenesis, so that individual pedons occupy only a narrow range in feature space, and interpretations for land use or properties used for modellingmodeling can use a narrow range of attribute values.

It is well known that soil management by humans can change soil properties, and indeed an attempt was made by Amundson and Jenny (1991) to identify humans separately from other organisms as soil-forming factors. They developed an expanded state factor Eq. (1) conceptually describing the inter-dependence of the ecosystem, humans as individuals and humans in their cultural context on state factors:

$$h, c, a, v, s = f\,(o_h, c_i, cl, o, r, p, t, \ldots) \tag{1}$$

where the dependent variables *h*umans, their *c*ulture, *a*nimals, *v*egetation, and *s*oil are the result of factors *cl*imate, *o*rganisms considered as the natural vegetation, *r*elief, *p*arent material, the *t*ime these have been operating (and in the case of *cl* and *o* possibly changing over time), and, most notably, humans as a special kind of organism, o_h and their cultural inheritance c_i, which includes land uses systems and soil management techniques. This equation includes humans and culture on both sides of the equation: humans as a phenotype affected by soil on left (h) and humans as a cause of soil change on right (o_h); culture as

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affected by soil management on the left (c) and culture at various past time periods on the right (c_i).

In the case of intensive (e.g., deep ripping, additions of technogenic or transported materials) or long-term (e.g., additions of plaggen) management interventions, soil morphology and properties change enough to be recognized in soil classification systems as separate soil types. The anthropic factor of pedogenesis is considered to have caused a more or less permanent change. These classes should be distinct enough both in their properties and geographic associations to be reliably mapped. Examples are the Technosols (Rossiter, 2007) and Anthrosols reference groups of the WRB, the soil series established for urban soil surveys in New York City (Hernández and Galbraith, 1997), and the paddy rice soils (similar to WRB Stagnic Anthrosols) of Chinese Soil Taxonomy (CST) (Cooperative Research Group on Chinese Soil Taxonomy, 2001; Gerasimova, 2010).

However, most soil management interventions are not so extreme as to be recognized as a permanent change in the soil, yet some have clear effects on *soil functions*, defined in terms of: (i) biomass production, including agriculture and forestry; (ii) storing, filtering and transforming nutrients, substances and water; (iii) biodiversity pool, such as habitats, species and genes; (iv) physical and cultural environment for humans and human activities; (v) source of raw materials; (vi) acting as C pool; and (vii) archive of geological and archeological heritage (European Commission, 2006, Ch. 1, Art.1). The designers of genetically-based soil classification systems such as Soil Taxonomy do not use soil properties that are easily changed by humans at the higher levels of their classifications, if at all.

Twenty years ago Droogers and Bouma (1997) suggested the terms *genoform* and *phenoform* for this situation, using simulation modeling to relate field-identified phenoforms to water relations, organic matter, solute and heat dynamics, and crop growth. This followed several studies in the Netherlands (Kooistra et al., 1985, 1984; van Lanen et al., 1987; Vos and Kooistra, 1994) some years earlier of soil structure differences and associated physical properties within single mapping units of the Dutch 1:50 000 soil map, and associated differences in soil function. In the study of van Lanen et al. (1987) soils under permanent grassland and those used for market gardens showed strong differences in field soil structure, pore size and shape (as evaluated in thin sections), soil hydrological functions including bypass flow, hydraulic conductivity, soil water retention and pore connectivity, and, most importantly, land qualities including workability and water deficit.

Genoforms were implicitly defined by Droogers and Bouma (1997) as pedons of the dominant genetic soil type within map units. *Phenoforms* were implicitly defined as areas within a genoform where the soil properties had been sufficiently changed by management to affect soil functions. Their specific example was a map unit with the genoform identified as a Soil Taxonomy *loamy, mixed, calcareous, mesic Typic Fluvaquent*, map unit Mn25A in Zeeland (NL), “calcareous polder vague soils with a sandy loam surface layer” in the Dutch system (de Bakker, 1979). Three different phenoforms of this map unit were identified by soil surveyors. To do this they made observations in certain fields, all mapped as the Mn25A genoform, indicated by farmers as having a particular land use history, in this case three long-term management regimes: biodynamic crop rotation, conventional crop rotation, and permanent meadow. These showed distinct differences in topsoil properties, structure, soil hydrology, and rooting patterns, so that their soil functions related to soil water storage, movement, infiltration, redistribution and plant uptake were substantially different. Table 1 shows the large difference in topsoil properties related to soil hydrology, notably the much higher bulk density, lower organic matter, and porosity of the conventional temporary grassland. These soils had strong coarse prismatic or blocky structure, as opposed to weak fine granular structure in the permanent grassland. These physical differences were used to identify the phenoforms in the field. By applying a dynamic simulation model to predict yields for 30 years, the authors showed that the crop production soil function was substantially different among these phenoforms, and that this was because of large differences in the storing and filtering soil function. The same research group followed this work up with more evidence of phenoforms (Droogers et al., 1997; Bouma and Droogers, 1999; Bouma et al., 1999) However, these *ad hoc* identifications of phenoforms do not constitute a rigorous definition.

Table 1
Topsoil properties, mean 10–30 cm; after Table 1 of Droogers and Bouma (1997).

Management	Bulk density Mg m $^{-3}$	Organic matter g kg $^{-1}$	Porosity m^3 m $^{-3}$
Biodynamic, temporary grassland	1.47	33	0.42
Conventional, temporary grassland	1.68	17	0.36
Conventional, permanent grassland	1.38	50	0.46

All differences are significant at $p = 0.05$.

Kodesova et al. (2011) working in the Czech Republic, while not using the term *phenoform*, in fact identified these within a single soil type (WRB *Haplic Luvisols*) by comparing soil structure and soil hydraulic properties under different land management.

Recently, Stevenson et al. (2015) working in New Zealand advanced the discussion by relating phenoforms to “modification of dynamic soil properties through specific land use history”. These properties are those that can be easily affected by management, as opposed to relatively static properties which define the genoform; such properties have been selected to help land managers assess and monitor so-called *soil health* (Vargas Rojas et al., 2016; Moebius-Clune et al., 2017) or *soil quality* (de Paul Obade and Lal, 2016). These authors distinguish between phenoforms and new genoforms: the latter are when management has more or less permanently changed the static properties used for soil classification and conventional mapping, in which case new classes must be defined at the appropriate level. However, this does not address the time dimension: are changes in dynamic soil properties within a single crop cycle or rotation to be considered phenoforms? How persistent must the changes in dynamic soil properties be, and how difficult must it be to revert to their previous state?

The newest version of the USDA Soil Survey Manual (Soil Survey Division Staff, 2017) includes a chapter on dynamic soil properties and soil change (Wills et al., 2017). This describes a method for recording dynamic properties at sample points and using these to characterize map units containing the points, especially with reference to known “benchmark” sites, using the space-for-time substitution method to assess soil change under management or environmental variations. Indicator properties are selected which are thought to be closely related to soil functions. However, it does not propose to separate map units according to dynamic properties, nor does it distinguish between short- and medium-term dynamic properties.

The idea to define and map dynamic soil properties is also found in recent efforts in topsoil classification and humus form identification (Jabiol et al., 2013; Fox et al., 2014; Delft et al., 2006); see Section 3.1.

Although the original concept of phenoforms was based on soil physical differences, certain soil chemical differences caused by management within a genoform can affect soil function. Some of these also cause substantial physical differences, e.g., continued addition of irrigation water with high Na^+ concentrations leading to deflocculation and structure change, or long-term additions of compost or manure leading to higher concentrations of organic matter and changed soil structure. These would be included in the original phenoform concept, since the physical effects would be evident. However, some management-induced chemical differences do not affect physical properties but do affect soil function, e.g., pollution by heavy metals or P saturation by fertilization. We would like to include these in the phenoform concept.

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