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Modeling soil genesis at pedon and landscape scales: Achievements and problems

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ABSTRACT

Modeling soil evolution is an important step towards understanding the complexity of the soil system and its interaction with the other systems. The major challenge confronted by pedologists until now is the ability to develop models capable of describing the complete complexity of the soil system. This paper presents the state of art overview of such a soil evolution model, SoilGen, its applications and limitations. In addition, the paper gives an overview of how the SoilGen model may be linked to landscape evolution models to model soilscape development. SoilGen is a mechanistic pedogenetic model in which soil forming processes such as clay migration, decalcification, carbon cycling, bioturbation, physical and chemical weathering coupled with water flow are simulated at multi-millennium time scale. The model has been calibrated and undergone extensive field testing, giving reasonable results at both pedon and landscape scales. However discrepancies between observed and simulated soil properties such as base saturation (BS), cation exchange capacity (CEC) and pH have been reported. These have been attributed partly to simplification of soil forming processes particularly in the weathering and chemical systems. There is therefore a need to extend the description of chemical and weathering systems in the SoilGen model. These extensions will not only improve model performance but will also enlarge its application range in simulating the genesis of typical features of more than half of the WRB-Reference Soil Groups. We also note here that although landscape evolution models have been successfully applied to model soil production and distribution, simplified and/or incomplete description of soil forming processes remain major limitations. We therefore add to the voices in scientific literature calling for integration of pedon and landscape scale models. In addition there is critical need for high quality chronosequence, climosequence, and toposequence profile datasets to enhance calibration and validation of soil evolution models.

1. Introduction

Soil genesis is an important subject linking soil science to other scientific fields. The processes involved in soil formation provide an understanding of the interactions between the atmosphere, hydrosphere, lithosphere, and the biosphere. It is the interactions among these systems (termed as foundation for earth system science) that define the existence of life on terrestrial ecosystems as they influence nutrient cycles, energy budgets, hydrological cycle and ecosystem productivity (Nooralla, 1999). Various studies have demonstrated the importance of soil formation processes including mineral weathering in regulating the earth's surface temperature by consuming carbon dioxide (Ferrier et al., 2010; Violette et al., 2010). In addition, these interactions provide a foundation for assessing influence of human activities on global environmental change (Nooralla, 1999).

Despite the importance of soil genesis, our knowledge of soil evolution remains limited compared to that of plant and animal growth (Stockmann et al., 2011). Nevertheless, the development of soil genesis models (pedogenesis models) has generally enhanced our understanding of soils over the last few decades. The reasons behind the development of pedogenesis models are numerous. Pedogenesis models are useful tools to understand the complexity of soil systems (Stockmann et al., 2011). These models are also indispensable to be able to quantify the response of soil forming processes to the Jenny (1941) pedogenetic factors ("CLORPT") i.e. climate, organisms, relief, parent material and time (McBratney et al., 2003; Godderis et al., 2010; Finke, 2012). In addition

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pedogenesis models provide an opportunity to interpolate in time soil characteristics for different applications e.g. in landscape reconstruction and archeological land evaluation (Zwertvaegher et al., 2010). Other motives for soil evolution models include assessing the effects of global change on ecosystems, to improve our knowledge of soil forming processes (Salvador-Blanes et al., 2007) and to evaluate if reconstructed soils would develop into the soils that we observe in the present time (Finke, 2012).

The above motives have prompted the development of various pedogenesis models. These models have been developed for specific purposes ranging from digital soil mapping, soil production, and redistribution studies to biogeochemical studies. The detailed history of development of soil evolution models has been presented in previous studies (Minasny et al., 2008; Samouëlian and Cornu, 2008; Stockmann et al., 2011; Samouëlian et al., 2012) and therefore not discussed here. In general, pedogenesis models have been categorized into either functional or mechanistic models. Briefly, functional models are those models that are mainly aimed at describing pedogenetic factors although they can also be based on the empirical equations (Stockmann et al., 2011). The development of such models dates back into the 19th century, the most cited one being Jenny (1941) who described soil formation as a function of "CLORPT" factors. Other functional pedogenesis models are those developed by Brimhall et al. (1985) and Phillips (1993).

As knowledge of soil science improved and was based on the functional approaches, the development of mechanistic models started. Mechanistic pedogenesis models are those that are based on process-describing mechanisms formulated in the form of mathematical equations (Hoosbeek and Bryant, 1992; Stockmann et al., 2011). According to Stockmann et al. (2011), the idea of mechanistic soil modeling at landscape scale was first proposed by Huggett (1975). The first comprehensive mechanistic approach of soil profile development was presented by Kirkby (1977) and later developed by Kirkby (1985). Mechanistic models can be divided into two; those that focus on landscape scales (e.g. Dietrich et al., 1995; Minasny and McBratney, 1999, 2001; Schoorl et al., 2002; Samouëlian and Cornu, 2008) and those that focus on pedon scale (e.g. Mayer et al., 2002; Goddéris et al., 2006; Finke and Hutson, 2008; Sommer et al., 2008; Finke, 2012). The summary of the principles of most of these models is provided in the review by Stockmann et al. (2011).

According to Samouëlian et al. (2012), most of the above soil modeling approaches do not include water flow yet water flow is key to soil evolution. The other drawback for most of these approaches is that they have mainly focused on individual soil forming processes (e.g. solute transport, soil acidification, heat transport and mineral dissolution) rather than the simultaneous occurrence and interactions of various soil forming processes (Salvador-Blanes et al., 2007; Samouëlian et al., 2012). The application of most of these models in soil evolution studies has been limited due to their incomplete coverage of soil formation processes and their inability to take into account all the soil forming factors (Finke, 2012). In addition models simulating soil evolution over millennia-time scales are limited (Schaetzl and Schwenner, 2006; Finke, 2012).

The SoilGen model (Finke and Hutson, 2008; Finke, 2012) is one of the few complete soil evolution models identified in a review by Samouëlian et al. (2012). The model in essence couples all the three interacting processes of soil formation i.e. biological, geochemical, and physical processes. These three processes have been described in Samouëlian and Cornu (2008) and Samouëlian et al. (2012) as processes that must be included in a model that simulates soil evolution at different climate and land use scenarios. Furthermore, the SoilGen model is able to simulate soil formation over multi-millennium time scale.

The objectives of this study are (1) to provide the state of art overview of the SoilGen model (simulated soil forming processes, model data input), (2) to explain calibration strategies and model quality tests, (3) to discuss field applications and limitations of soil genesis models at pedon and landscape scales, and (4) to contribute to future perspectives of pedon and landscape soil modeling.

2. The SoilGen model

SoilGen 2.16 (Finke, 2012) is a pedon scale soil evolution model developed to simulate vertically discretized change in soil properties over millennium time scale. Essentially, SoilGen is a water flow driven, process-based soil model in which factors of soil formation ("CLORPT") are taken into account (Table 1). Major soil forming processes such as clay migration, decalcification, physical/chemical weathering, bioturbation, chemical equilibria and carbon cycling are simulated in SoilGen. In addition, SoilGen simulates the impact of human activity on soil formation by taking into account fertilization and plowing and incorporating the effect of erosion and deposition (Table 1). The model has been calibrated and successfully applied in a number of field case studies (Finke, 2012; Sauer et al., 2012; Yu et al., 2013). We describe briefly governing processes in SoilGen 2.16, calibration and application case studies in the subsequent sections. For a detailed description of the SoilGen model, reference should be made to Finke and Hutson (2008) and Finke (2012).

Table 1
Factors of soil formation and their link to soil forming processes simulated in the SoilGen model.

Factor of soil formation		SoilGen governing processes
Climate	Temperature	Heat flow[a]
	Precipitation: water	Water flow[a]
	Precipitation: solutes	Solute flow[a]
	Evaporation	Evapotranspiration[a]
Organisms	Vegetation	C-cycling[b] CO_2 production and diffusion Cation uptake and release Root distribution
	Fauna	Bioturbation
	Human influence	Fertilization[a] Plowing/tillage
Relief	Slope	Runoff[a]
	Erosion/sedimentation	Removal or addition of top layers
	Local variants of T, P, and E	Heat/water/solute flow with P and E as f (exposition)
Parent material	Texture	Dissolution/precipitation[a] Bioturbation C-cycling Physical weathering Clay migration CEC as an f(clay, OC)
	Mineralogy	Cation release from chemical weathering[c]
	Solute and exchange chemistry of Ca, Al, Mg, Na	Chemical equilibria[a] Cation exchange equilibria[a] Arrhenius temperature correction Al-Gibbsite equilibrium Exchangeable acidity Base saturation
Time	Change of boundary conditions	

T, P and E are Temperature, precipitation, and evapotranspiration, respectively.
Source: Adapted from Finke and Hutson (2008) and Finke (2012).

[a] Based on LEACHC code (Hutson, 2003).
[b] Based on RothC 26.3 (Coleman and Jenkinson, 2005).
[c] Based on NUCSAM (Kros, 2002).

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2.1. SoilGen governing processes

2.1.1. Water, solute and heat transfer

Transfer modules should be present in a pedogenesis model if such a model has to predict the impact of land use and climate in soil formation (Samouëlian et al., 2012). In SoilGen, the transfer of water, solute, and heat through the soil profile is simulated following the concepts in the LEACHC code (Hutson, 2003). Unsaturated vertical water flow is described using Richards' equation while the heat flow equation is used to simulate heat and temperature distribution in the soil profile. In case of frozen conditions (soil temperatures below 0 °C), hydraulic conductivity is reduced by an impedance factor, Ω (Finke and Hutson, 2008). Transfer of solutes is described using the convection–dispersion equation (CDE). In addition, the diffusive flow of CO_2 is simulated. Detailed description of these processes is given in Finke and Hutson (2008).

2.1.2. Weathering processes

The SoilGen model describes two weathering processes (physical and chemical) as primary mechanisms by which soil is formed from the parent material/saprolite. Properties (e.g. texture, Carbon percentage, mineralogy) of the parent material (C-horizon) are assumed as initial conditions at the start of the simulations. These properties will evolve over time as influenced by different soil forming processes (e.g. weathering) and factors ("CLORPT"). Physical weathering is modeled as a function of temperature and it leads to the reduction in grain size consequently producing clay sized material that can be moved by processes such as clay migration. Reduction in particle size also increases surface area thus enhancing dissolution of minerals (chemical weathering). Chemical weathering of primary minerals in the model represents the major source of cations in non-agricultural soils. This process therefore influences soil solution concentrations and equilibrium reactions. Pools of cations (amounts of primary minerals) reduce over time as weathering continues. We briefly explain how physical and chemical weathering processes are described in SoilGen. For detailed descriptions of these processes reference should be made to Finke (2012).

2.1.2.1. Physical weathering. Finke (2012) describes physical weathering as the process that breaks up soil particles due to strain caused by temperature gradients usually associated with fluctuations in thermal expansion inside the particle, by ice growth or growth of other crystals of larger size than the porosity permits. The net effect of the physical weathering process is a reduction in grain size, consequently producing material in the clay fraction that may be moved by clay migration.

As in Salvador-Blanes et al. (2007), physical weathering in SoilGen is modelled as a probabilistic process with a clear connection to soil temperature gradients in the SoilGen approach. The fine earth fraction is divided into particle size classes with boundaries at 2048-1024-512-256-128-64-32-16-8-4-2 μm (i.e. class boundaries are powers of 2). The major assumption is that all particles are cubes with a ribbon size halfway between the class limits: 1536, 768, 384, 192, 96, 48, 24, 12, 6, 3, and 1 μm. Therefore, each particle needs to be split in half up to 7 times to obtain 8 equally sized particles in the next smaller particle size class. The splitting probability of a particle, P_s is assumed to follow Bernoulli process and it depends on the temperature gradient over a certain time interval, d*t* (Finke, 2012):

$$P_s = \begin{cases} P_{s,\max} & \text{if } \dfrac{dT}{dt} > B \\ \dfrac{P_{s,\max} * \dfrac{dT}{dt}}{B} & \text{if } \dfrac{dT}{dt} \le B \end{cases} \qquad (1)$$

where $P_{s,\max}$ is the maximal split probability. *B* is a threshold temperature gradient over d*t* where $P_{s,\max}$ becomes maximal and *T* is the temperature. In the study by Finke (2012), $P_{s,\max}$ was subjected to calibration while *B* was fixed to a value of 1 °C h^{-1}.

The expected number *E* (*N*) of the potential splitting events required to achieve successful splits, *m* (i.e., $m = 7$) are assumed to follow the negative binomial distribution and are described as:

$$E(N) = \frac{m}{P_s} \qquad (2)$$

Therefore, the number of grains, *S* in any particle size class *i* that is split in time d*t* is calculated as:

$$S_{i,dt} = \min\left(k_{i,t-dt}, k_{i,t-dt}/E(N)\right) \qquad (3)$$

where $k_{i,t-dt}$ represents the number of grains in particle size class at the start of dt and $k_{i,t}$ is described as:

$$k_{i,t} = k_{i,t-dt} - a * S_{i,dt} + b * 8 * S_{i-1,dt} \qquad (4)$$

where $a = 0$ for clay fraction ($i = 11$) and $a = 1$ else; $b = 0$ for the coarsest sand fraction ($i = 1$) and $b = 1$ else (Finke, 2012).

The breakup of bedrock (e.g. by plant roots) and the splitting of gravel-sized particles is not yet included in the description of physical weathering, this currently limits application of the SoilGen model to unconsolidated, non-gravelly deposits.

2.1.2.2. Chemical weathering of primary minerals. In SoilGen, Anorthite, Chlorite, Microcline and Albite primary minerals are taken as major pools of Ca, Mg, K, and Na, respectively. The weathering flux, FX ($mol_c ha^{-1} y^{-1}$) of cation X from the primary mineral into the soil solution is described as in (Kros, 2002):

$$FX = \rho * T * kX * (\theta cH)^{\alpha(X)} * cX \qquad (5)$$

where ρ is dry soil bulk density (kg m^{-3}), *T* is soil compartment thickness (m), *kX* is a weathering rate constant (m^3 mol_c^{-1} y^{-1}) for cation *X*, *cH* is the hydrogen concentration (mol_c m^{-3}), θ is water content (m^3 water m^{-3} soil), a modification introduced in SoilGen to convert hydrogen concentration to volume basis (i.e. mol_c H m^{-3} soil), α(X) is dimensionless and it is a parameter describing the effect of pH on weathering rate, and *cX* is the content of element *X* in the primary mineral (mol_c kg^{-1}).

Congruent weathering of Anorthite, Chlorite, Microcline and Albite is used to model the weathering flux of Al (FAl) from primary minerals (Kros, 2002; Finke, 2012):

$$\text{FAl} = 3\text{FCa} + 0.6\text{FMg} + 3\text{FK} + 3\text{FNa} \qquad (6)$$

2.1.3. Clay migration

The clay migration process is described by detachment, dispersion, transportation and filtering sub-processes. The process is initiated at the surface by splash detachment that brings part of the clay in the top soil compartment in the transportable state. Mechanical impact and low solute concentration of raindrops both bring clay in a transportable state at the soil surface. At any depth in the soil, clay can be dispersed when the solute concentration falls below a threshold value, and then also enters a transportable state. Thus, the clay migration process starts at the surface, but it can occur at any depth of the soil profile depending on the solute concentration (Finke, 2012). Splash detachment is modelled based on the approach of Jarvis et al. (1999) but modified by Finke (2012) to include the reducing effect of a humus profile and a vegetation cover on splash detachment and the effect of bioturbation on redistribution of clay.

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Thus, at the surface the mass balance of dispersible particles is computed as:

$$\frac{dA_s}{dt} = -D + P \tag{7}$$

where A_s is the mass of dispersible particles at the soil surface (g m^{-2}), D and P represent the splash detachment rate (g m^{-2} h^{-1}) and the replenishment rate (g m^{-2} h^{-1}), respectively.

A_s is a function of cation exchange capacity (CEC), clay fraction and organic carbon (OC), (Eq. (8)). The maximal dispersible clay, DC_{max} (%), is first calculated based on the regression equations of Brubaker et al. (1992):

$$DC_{max} = \begin{cases} 0.635{*}\text{clay} & \text{if}(\text{CEC} - 3{*}\text{OC})/\text{clay} \le 0.4 \\ 0.340{*}\text{clay} & \text{if}(\text{CEC} - 3{*}\text{OC})/\text{clay} > 0.4 \end{cases} \tag{8}$$

The parameter A_s is finally calculated as:

$$A_s = DC_s{*}\rho{*}0.01 \tag{9}$$

where DC_s (g g^{-1} soil) is the amount of readily available dispersible particles at the soil surface (1 mm) with its initial value set equal to DC_{max}, ρ is the dry soil bulk density (kg m^{-3}) and 0.01 is the unit conversion factor.

The parameter, D in Eq. (7) is computed for each rainfall event as follows:

$$D = k_d{*}E{*}R{*}(1 - sc){*}DC_s \tag{10}$$

Where k_d is the soil detachability coefficient (g J^{-1}) and it was set to the value of 15 by Jarvis et al. (1999) during calibration. sc is the dimensionless parameter accounting for the fraction of the soil surface that is covered by vegetation or the humus profile. R (mm h^{-1}) is rainfall intensity, and E (J m^{-2} mm^{-1}) is kinetic energy of the rainfall obtained from relation described in the revised universal soil loss equation (Brown and Foster, 1987):

$$E = 29{*}\{1 - 0.72{*}\exp(-0.05{*}R)\} \tag{11}$$

The replenishment rate, P in Eq. (7) is estimated following the procedure of Jarvis et al. (1999):

$$P = k_r{*}\left(1 - \frac{DC_s}{DC_{max}}\right) \tag{12}$$

where k_r is the replenishment rate coefficient (g m^{-2} h^{-1}) set to the value 0.1 as calibrated by Jarvis et al. (1999). In SoilGen, the value of P is restricted such that it does not exceed the amount present in the surface 1 mm layer after bioturbation (Finke, 2012).

The proportion of clay that is in a transportable dispersed state, fDC in every soil compartment is a function of the total electrolyte concentration, SC (mmol$_c$ dm^{-3} water) and critical salt concentration, CSC (mmol$_c$ dm^{-3} water) at which soil clay mixtures stay flocculated. SC and CSC are computed each time step and their threshold values are evaluated. The transportable dispersed clay then follows the CDE that is modified to include filtering as an additional sink term:

$$fDC = \{1 - (SC/CSC)\}{*}\theta_{macro}{*}fVC \tag{13}$$

where θ_{macro} is the volumetric water fraction (m^3m^{-3}) in macropores and it is estimated from the water retention curve at pressure head h (hPa) near saturation. fVC is the fraction of soil volume taken by clay. The parameter SC is estimated by the model every time step and CSC is determined by the model using simulated soil parameters and regression relation based on the experimental data from Goldberg and Foster (1990).

The filtering process (e.g. entrapment of clay particles in small pores) is modelled based on calculated pore water velocities using the equation given in Jarvis et al. (1999):

$$F = f_{ref}{*}v_{ref}^{n}{*}v^{1-n}{*}c{*}\theta \tag{14}$$

where f_{ref} (m^{-1}) is a reference filter coefficient, v_{ref} (m h^{-1}) is the pore water velocity at which f_{ref} is measured of which values of 2 m^{-1} at 0.1 m h^{-1} were taken from Jarvis et al. (1999) and used in SoilGen. The parameter v is the current pore water velocity and, c and n represent the particle concentration (g m^{-3} water) and an empirical exponent, respectively. In SoilGen, c is a vector containing the dispersible and transportable clay calculated using Eq. (13). This parameter also contains the associated exchangeable cations i.e., Ca, Mg, Na, K, H and Al (Finke, 2012).

2.1.4. *Cation exchange capacity*

The dynamics in soil cation exchange capacity (CEC) (e.g. due to clay migration and variation in organic matter content) is simulated using a 2-domain CEC model. The initial total CEC is partitioned into two: (1) portion attributed to the mineral fraction and (2) portion attributed to the initial soil organic carbon, OC (i.e., the amount of carbon in the parent material at the start of the simulation). The regression equation by Foth and Ellis (1996) based on the 12,000 data sets is used to determine the percentage contributions of OC (%) and clay (%) to the total CEC ($mmol^{+}$ kg^{-1}):

$$CEC = f{*}(32 + 36.7{*}OC + 1.96{*}Clay) \tag{15}$$

where f is a factor matching the empirical CEC after Foth and Ellis (1996) to the initial CEC in the simulated pedon. The constant in the regression equation accounts for cation exchange sites at particles larger than 2 μm, and may be also due to the choice of a linear regression model by Foth and Ellis (1996). According to Finke (2012), this approach is a simplification of reality as the possible effect of pH change on CEC is not accounted for.

2.1.5. *Soil chemical system and chemical equilibria*

Five phases (i.e. solution, precipitated, exchange, organic and unweathered phases) are categorized in the SoilGen model chemical system (Fig. 1). Dissolution of primary minerals (unweathered phase), decomposition of organic matter, atmospheric depositions and addition through fertilizers are considered as major processes through which ions are released into the soil solution. Uptake by plants, leaching and precipitation are processes through which these species leave the soil solution phase.

The soil solution phase is brought into equilibrium with precipitated and exchange phases by satisfying various solubility laws and rate constants that include: (1) Henry's Law constant for CO_2, (2) the dissociation constant of H_2CO_3, (3) the dissociation constant of H_2O, (4) the solubility constants of gypsum, calcite and gibbsite, (5) ion pair stabilities constants of different species in the soil solution and (6) Gapon selectivity constants for exchange/solution phase equilibriums for Ca–Mg–Na–K–H–Al. Instantaneous equilibrium is assumed because calculations are repeated at small time steps (usually a fraction of a day), with small water fluxes during those time steps, and so changes in chemical composition are expected to be gradual. Generally, the equilibration is done iteratively in 4 steps as described in detail by Finke and Hutson (2008), taking into account Arrhenius' temperature correction of all chemical constants.

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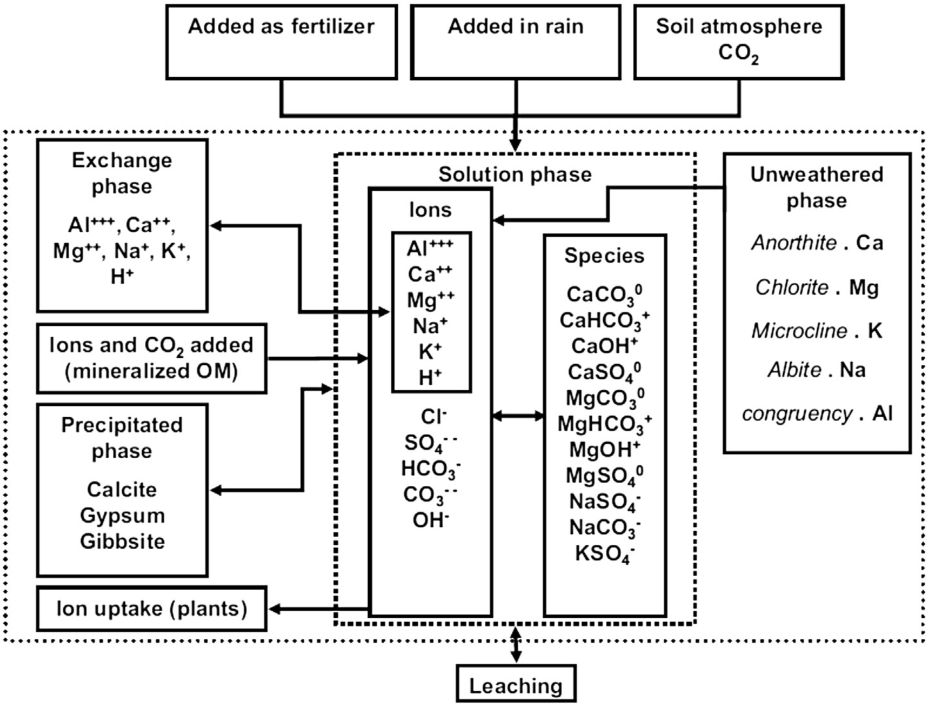

Fig. 1. Soil chemical system simulated by SoilGen (Source: Finke, 2012).

2.1.6. *Vegetation, carbon cycling and plant uptake processes*

The interaction between the soil and the vegetation in SoilGen, occurs mainly through annual litter input, carbon cycling and ion uptake (Fig. 2), and these depend on the vegetation type. Four vegetation types are distinguished (grass/scrub, agriculture, conifers and deciduous wood). Each of these vegetation types is characterized by a unique rooting density function, cation uptake, carbon decomposition rates and annual leaf and root litter input (Finke and Hutson, 2008).

Carbon cycling is simulated following the concepts of the RothC 26.3 model (Jenkinson and Coleman, 1994) where dead plant material is split into leaf litter and root litter. The root litter is further subdivided into resistant plant material (RPM) and decomposable plant material (DPM) (Fig. 2). Both RPM and DPM fractions degrade into microbial biomass (BIO), humus (HUM) and CO_2 at rates determined by the fraction that is decomposing as well as environmental factors like soil temperature, soil moisture deficit, soil cover fraction and the time increment (Finke and Hutson, 2008).

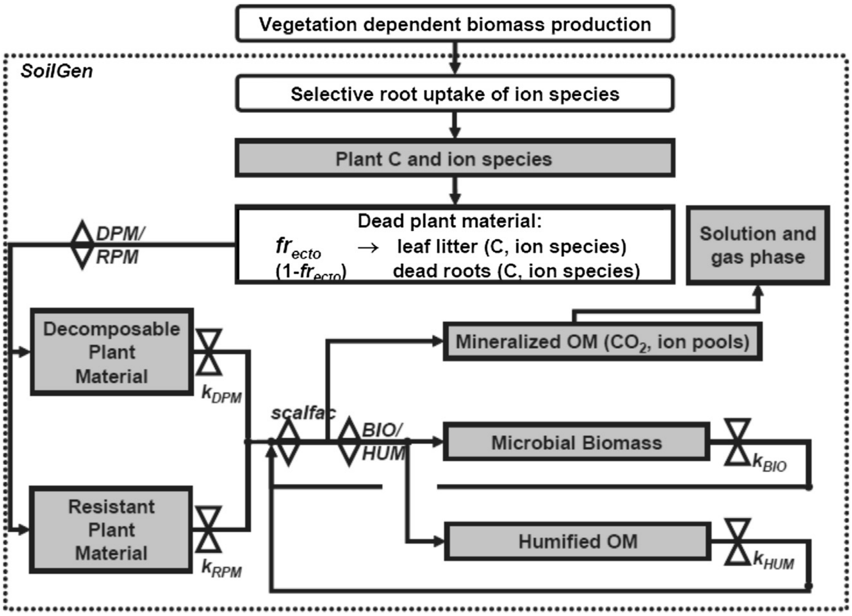

Fig. 2. Carbon cycling process as described in SoilGen (Source: Yu et al., 2013). Grey boxes represent carbon pools, ⧖ and ◇ indicate rate and distribution factors, respectively. The dotted line represents the process boundary.

The CO_2 produced at each time step (i.e. daily in SoilGen) enters into the gas regime equation. The distribution of CO_2 in the soil profile at the end of each day gives values of pCO_2 for the chemical equilibria of that day. Additionally, ions taken up by the plants follow the same decomposition pathways and are eventually released again in the solution phase (Finke and Hutson, 2008).

Cation (Al, Ca, Mg, Na, and K) uptake by vegetation is assumed to occur via the transpiration stream by preferential uptake to reflect the relative fractions of those elements measured in the plant. Therefore, each vegetation is characterized by a target content of these cations. Relative concentrations of Al, Ca, Mg, Na, and K for four vegetation types considered in SoilGen have been published (Finke, 2012, Table 2). The computation of cation and anion uptake in each soil compartment then follows a step by step procedure described in Finke and Hutson (2008).

Table 2

Basic data input to the SoilGen model. IC = initial condition, BC = boundary condition and SIM = simulated input.

Soil forming factor	Input parameter	Units	Condition	Mandatory
Climate	Air temperature	°C	BC, SIM	Yes
	Precipitation	mm y^{-1}	BC	Yes
	Potential evapotranspiration	mm y^{-1}	BC	Yes
Organisms	Vegetation type	–	BC	Yes
	C-input (litter, organic manure)	1000 kg ha^{-1} y^{-1}	IC	Yes
	Bioturbation	1000 kg ha^{-1} y^{-1}	BC	No
	Erosion/Sedimentation	1000 kg ha^{-1} y^{-1}	BC	No
Relief	Slope	°	IC	Yes
	Slope exposition	°	IC	Yes
	Wind direction	°	IC	Yes
Parent material	Clay/Silt/Sand	Mass %	IC, SIM	Yes
	OC	Mass %	IC, SIM	Yes
	Ca, Mg, Na, K, Al, SO4, Cl, Alkalinity in solution	mmol dm^{-3}	IC, SIM	Yes
	Ca, Mg, Na, K, Al, H on exchange complex and CEC	$mmol^{+}$ kg^{-1}	IC, SIM	Yes
	$CaCO_3/CaSO_4$	Mass %	IC, SIM	Yes
	Gapon exchange coefficients	mol dm^{-3}	IC, SIM	Yes
	Ca, Mg, Na, K, Al in primary minerals	mol^{+} kg^{-1}	IC, SIM	Yes
	Weathering rates of cations (Ca, Mg, Na, K, Al)	m^3 $molc^{-1}$ y^{-1}	IC	Yes
	Parameter describing effect of pH on Weathering rate	–	IC	Yes

2.1.7. *Soil phases redistribution processes*

In addition to physical weathering and clay migration processes described earlier, SoilGen considers bioturbation, tillage, erosion, sedimentation and, dissolution and precipitation of calcite and gypsum as other processes that lead to redistribution of soil phases (solid and liquid) in the soil profile. When simulating these redistribution processes, the central assumption of constant volume of each compartment with time is made. This is a simplification of reality because soil volume may increase in response to biological processes like burrowing of animals or collapse as a result of processes like decalcification and clay migration. In the terminology of Brimhall and Dietrich (1987) collapse corresponds to a strain of <0 and expansion to a strain >0, and the SoilGen model assumes a strain = 0. The errors introduced by this simplification may not affect the calculated mass percentages, but may have influence on some soil physical properties (Finke and Hutson, 2008).

Bioturbation is described as an incomplete mixing process. First, the fraction of the mass subject to vertical redistribution by soil meso and macro-fauna in each compartment is determined. This percentage is an input in SoilGen and it is made to vary over time with respect to vegetation, climate and soil depth (Finke and Hutson, 2008). The input mass fraction is used to vertically mix and redistribute soil masses to the bioturbated soil compartments (each compartment thickness is set to 50 mm). Secondly, the resulting mass in each compartment, consisting partly of a bioturbated mixture and partly of the original content, is horizontally (1 × 1 m area) mixed within the same compartment. This gives a new set of soil properties per soil compartment (Finke and Hutson, 2008). In addition, the effect of tillage is considered as an extreme form of bioturbation, where the mass fraction involved in the turbation is set to 50% over the plowing depth as determined by Ullrich and Volk (2009).

Erosion and sedimentation processes are currently implemented as inputs to the SoilGen model. In essence, erosion and sedimentation processes respectively remove and add entire soil compartments at the surface of the soil profile. History of the occurrence of these processes is needed as input to the model and this holds also for the composition of the added sediment.

2.1.8. *Coupling the effect of slope/exposition on precipitation and evapotranspiration*

To model the effect of relief ('R' factor) on soil formation, precipitation and evaporation inputs are corrected for slope and exposition in SoilGen. First the wind speed in the direction of the slope, V_2 (m s^{-1}) is calculated (Eq. (16)) based on the approach by Mauersberger (2001). V_2 together with the mean fall velocity of raindrops, v_r (set to 5 m s^{-1} in SoilGen: Finke, 2012) are used to calculate the diversion angle, β (degrees) from the vertical rainfall induced by wind (Eq. (17)). Finally, the net amount of rainfall, R_2 (mm) on a unit sloped area is obtained by correcting the precipitation at the horizontal plane for slope angle, diversion angle and the bearings of these two angles (Eq. (18)) (Finke, 2012).

$$V_2 = V_1 * \cos(\delta - \gamma) \tag{16}$$

where V_1 is the wind speed in wind direction, δ and γ are the upslope bearing and the wind bearing (in degrees), respectively.

$$\beta = \text{abs}\left(\arctan\left(\frac{V_2}{v_r}\right)\right) \tag{17}$$

$$R_2 = R_1(1 + \tan(\beta) * \tan(\alpha)) * \cos(\delta - \gamma) \tag{18}$$

where R_1 (mm) is the precipitation at the horizontal plane.

Net potential evapotranspiration PE_{net} is obtained by correcting the measured potential evapotranspiration PE_m for latitude, slope angle and slope azimuth. This is done with the assumption that potential evapotranspiration responds linearly to differences in incoming radiation for different slopes. The correction factor is therefore the ratio between the potential solar radiation on a horizontal surface at given latitude, summarized for one year, and the potential solar radiation on a slope with upslope bearing converted to map area for the same period (Finke, 2012). This ratio is calculated with an implementation of an algorithm developed by Swift (1976).

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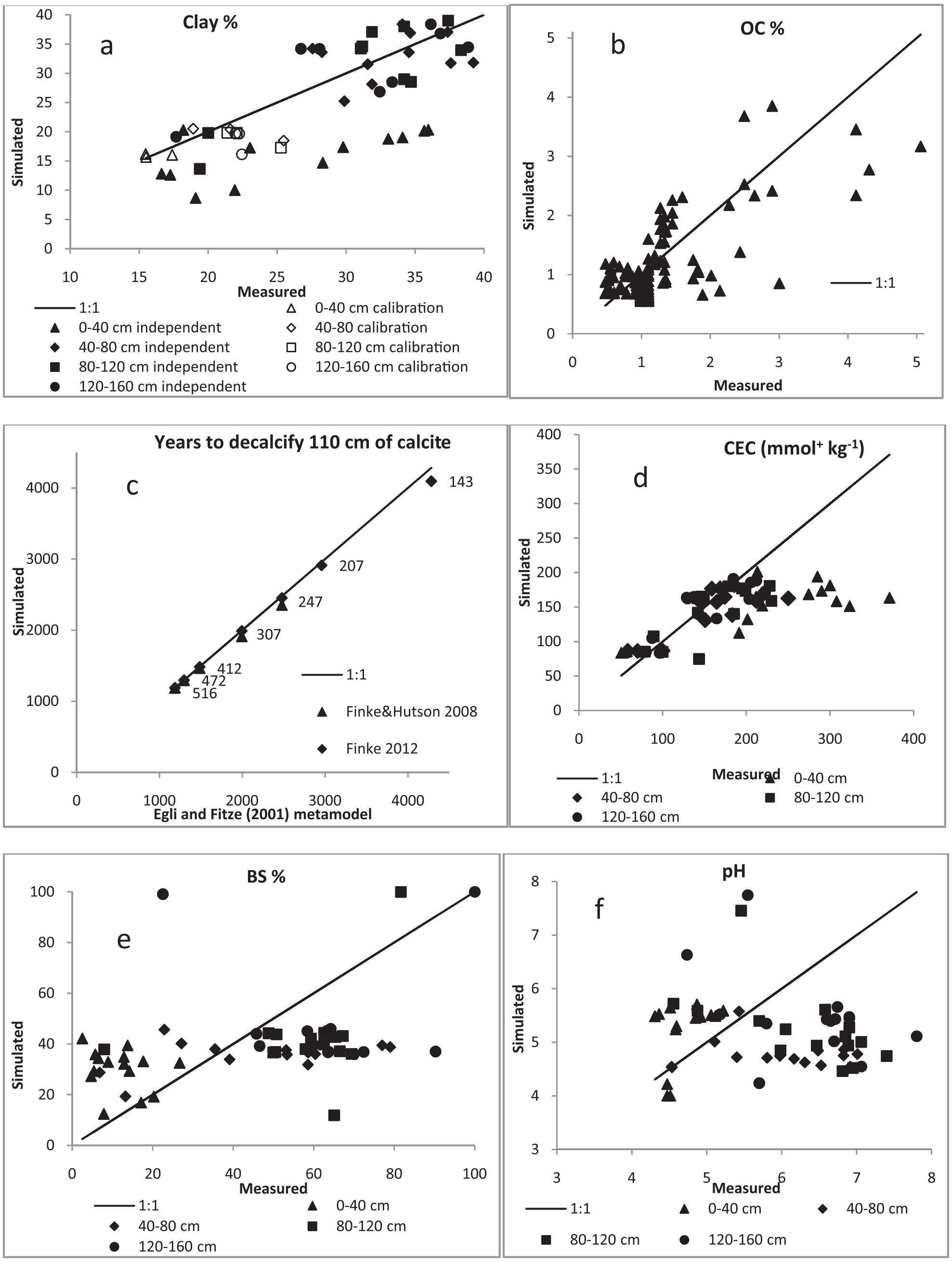

Fig. 3. SoilGen calibration tests for (a) clay migration (b) carbon cycling (c) decalcification and (d, e, f) degree of leaching. Measurements of OC were obtained from 6 different locations with sampling done at 5 cm interval for a depth 0–100 cm. Notice quite good simulations for clay percentage, Carbon percentage, decalcification rate but poor results for BS and pH.

2.1.9. *SoilGen time scale and time steps*

The SoilGen model simulates soil forming processes over a multi-millennium timescale (up to 15,000 years). However different soil forming processes operate at different time scales ranging from milliseconds (e.g., transport processes) to thousands of years (e.g., weathering) and this has to be taken care of. In the SoilGen model, heat flow and physical weathering are calculated at hourly time steps. Chemical and transport processes are calculated at time steps of milliseconds to hours, while mineral weathering and organic matter accumulation are calculated at daily time steps. Events such as bioturbation, erosion/sedimentation and fertilization are incorporated in the model at yearly time steps. All the outputs are however reported after every one year. More description of the SoilGen model temporal scales and processes time steps is given in Finke and Hutson (2008) and Finke (2012).

2.2. *SoilGen data input*

Factors of soil formation (‘CLORPT’) are linked to SoilGen as input parameters (Table 2). These inputs can be introduced as initial conditions (IC) or boundary conditions (BC). Some of these inputs (e.g. soil temperature, texture, OC) are also simulated/updated (SIM) within the model for use in the next time steps (Table 2). Initial conditions specify the soil (or sediment) at the start of the simulations, and properties are usually taken from C-horizons of analyzed soils. Properties at the end of the simulations can be

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compared to soil analysis for model calibration or validation. Slope and wind direction are input to assess the effect of local topography on precipitation and potential evapotranspiration. The other data input (e.g. bioturbation, erosion and sedimentation) is required if the effects of such factors are to be investigated. These are therefore not mandatory and may not be introduced to the model. The factor time ('T', not shown in the table) is captured in the model by constant updating of all the other input parameters based on the time steps. We summarize in Table 2, the basic data input to the SoilGen model, indicating whether it is mandatory or not. Temperature and potential evaporation are introduced into the model as weekly averages while daily values are needed for precipitation. Vegetation type, litter/manure, bioturbation, erosion and sedimentation are all annual inputs to the model. In addition, other detailed soil profile information (e.g. soil texture, bulk density, pCO_2, BS, CEC, moisture content) is necessary for model calibration and validation.

Furthermore, additional constants need to be provided to complete the description of some processes (Table 3). These constants are currently given as default values in SoilGen and are only adjusted during calibration. The user may change these values whenever necessary.

Table 3
Additional input parameters required to describe some soil forming processes in SoilGen. DPM and RPM = decomposable and resistant plant material, respectively. BIO = microbial biomass and HUM = humus.

Soil forming process	Input parameter	Units
C-cycling	DPM/RPM ratio	–
	Fraction of litter that is from leaf (per vegetation type)	–
	Fraction of litter that is from root (per vegetation type)	–
	Fraction of precipitation that is intercepted (per vegetation type)	–
	Decomposition rate constants of DPM, RPM, BIO and HUM	–
	Distribution ratios (BIO/HUM and CO_2/(BIO + HUM))	–
Physical weathering	Maximum splitting probability	–
	Temperature gradient where splitting probability becomes maximal	°C h^{-1}
Clay migration	Soil detachability coefficient	g J^{-1}
	Replenishment rate coefficient	g m^{-2} h^{-1}
	Pressure head at which macro-pores are empty	hPa
	Filtering coefficient	–
	Reference filter coefficient, fref	m^{-1}
	Pore water velocity at which fref is measured	m h^{-1}
	Bulk density of ectorganic layers	kg dm^{-3}
	Thickness of ectorganic layer at which no splash occurs	mm
	Montmorillonite content in clay fraction	%
	2:1 clay mineral content	%

2.3. SoilGen model calibration and quality tests

Calibrating a model entails a systematic process of modifying the input parameters to a model until the best match between model simulations and observations is obtained (Yu et al., 2013). The calibration process can also be done by reproducing observed values already observed in literature. The usual way to calibrate the model is to identify sensitive parameters (sensitivity analysis) as a first step. Due to large runtimes and many processes described, calibration in SoilGen has followed a step by step procedure in which processes have been calibrated independently. Processes that have been calibrated in SoilGen include physical weathering in combination with clay migration (Finke, 2012), decalcification (Finke and Hutson, 2008; Finke, 2012; Zwertvaegher et al., 2013) and carbon cycling (Yu et al., 2013). In most cases, calibration compared the simulated final state of the soil to present measurements. Calibration focused on process parameters and not on the initial conditions or boundary conditions along the time line, although these are also associated with uncertainty. We briefly describe each of the approaches followed in calibrating these processes.

2.3.1. Physical weathering and clay migration

The maximal physical weathering factor (P_s), filtering factor (n) and hydraulic head at which macro-pores empty (h) were the parameters identified for calibration of the physical weathering and clay migration processes. The calibration was done by adjusting these parameters to match the profile texture distribution (Finke, 2012). The test model runs were first done to identify the possible range of each of the 3 parameters. The model was run for 14 different combinations of P_s, n and h parameters. Each time the model outputs were confronted with the observations to quantify accuracy of the simulations. Then, a polynomial function was fitted that predicts the simulation accuracy as a function of the parameter values of P_s, n and h. The position in parameter space with optimal simulation was predicted by analyzing the partial derivatives of the fitted polynomial function. The found parameter combination is then tested with one more simulation to check if this combination does give the best results. According to Yu et al. (2013), this approach is suitable for long runtime models like SoilGen, but it may not find the true optimal parameter set. Calibration tests (Fig. 3a) showed that clay percentage distribution over depth was quite well reproduced. The model however underestimated clay percentage (i.e. predicted very strong clay eluviation) at the top layer (0–40 cm).

2.3.2. Carbon cycling

The SoilGen carbon module was calibrated for the Belgian loess soils under permanent deciduous forests and for the Chinese loess soils under secondary deciduous forests (Yu et al., 2013). Prior to calibration, Yu et al. (2013) performed a sensitivity analysis (SA) following Morris (1991) method. They identified decomposition rate factors of humus (k_{Hum}) and RPM (k_{RPM}), and the fraction of incoming plant material in form of leaf litter (fr_{ecto}) as the three most sensitive parameters. Because of long runtime, Yu et al. (2013) preferred another approach of minimizing the difference between measurements and simulations. Their calibration method involved calibrating each of the three identified sensitive parameters step by step starting with the most sensitive parameter. A possible range for each parameter was determined during SA and parallel tests were done. For each test, simulated results were confronted with measurements and evaluated based on model quality indicators like root mean square error (RMSE), mean difference (MD) and dissimilarity (DIS). The calibration of a given parameter was completed whenever the best result was <5% better than the second best. Their calibration results were consistent with previous studies and indicated that the calibrated SoilGen carbon module was able to reproduce measured carbon vertical distribution over time (Fig. 3b).

2.3.3. Decalcification rate

The decalcification process influences a number of soil properties including porosity, bulk density, cation content, pH and indirectly also water flow. It is therefore an important process that should be accurately constrained to minimize uncertainty in model results. Previous studies (Finke and Hutson, 2008; Finke, 2012; Zwertvaegher et al., 2013) have followed a similar calibration approach in which the dissolution constant of calcium carbonate (k_{SO}) was adjusted to match the decalcification speed values reported in Egli and Fitze (2001) based on an extensive field data set. In principal, the number of years needed to decalcify the upper 1100 mm of standard loess soil were calculated and compared with the value based on the study of Egli and Fitze (2001). The comparison was repeated for different values of k_{SO} and at a precipitation surplus of 472 mm yr^{-1} (Finke, 2012) or 247 mm yr^{-1} (Zwertvaegher et al., 2013). The k_{SO} with the best comparison was selected and then checked against values from Egli and Fitze (2001) for different precipitation surpluses. Calibration test results (Zwertvaegher et al., 2013) indicated that the SoilGen model reproduced the decalcification process with good accuracy at high and extremely very high precipitation surpluses but overestimation of decalcification was observed at low precipitation surpluses. This is partly based on the fact that the Egli and Fitze (2001) data set includes few low precipitation surpluses. Finke and Hutson (2008) and Finke (2012) also reported good agreement between Egli and Fitze (2001) results and SoilGen simulations (Fig. 3c). Best $\log_{10}$ k_{SO} values of −9.2 (Zwertvaegher et al., 2013) and −8.36 (Finke, 2012) were reported for precipitation surpluses of 247 mm yr^{-1} and 472 mm yr^{-1}, respectively (in sandy and silt loam soils, respectively).

2.3.4. Degree of leaching

In calibrating the degree of leaching, the fraction of rain intercepted by vegetation (P_{int}) was considered as the main factor influencing water percolation. The calibration approach involved adjusting P_{int} to match the measured values of BS (%), CEC and pH. Results showed fairly good estimation of BS % (Fig. 3e) but CEC (Fig. 3d) and pH (Fig. 3f) were poorly estimated.

2.4. SoilGen model field applications, limitations and future perspectives

2.4.1. Pedon scale applications

Finke and Hutson (2008) applied SoilGen to study the effect of varying climate on the formation of calcareous loess soils in Belgium and Hungary. The effects of bioturbation, vegetation and agriculture on soil formation from uniform calcareous loess parent material were also tested for the two areas. Calibration of decalcification rate was done prior to model application. Simulated soil properties included OC, calcite content, bulk density, clay dispersion indicator and pH. Results from this study demonstrated that decarbonization of the upper 1.2 m was completed in less than 2000 years under the Belgian leaching climate compared to the drier climate of Hungary in which decarbonization process was slow. In addition the clay migration process was more pronounced in the leaching climate of Belgium as compared to Hungary. Bioturbation slowed down the decarbonization processes by bringing sufficient calcite to the soil surface while keeping the pH high (Finke and Hutson, 2008). Agriculture through liming increased the calcite content in the soil, increased the soil pH and slowed down the clay migration process. Vegetation type influenced the distribution of exchangeable cations (e.g. K). Furthermore, Finke and Hutson (2008) observed that cations concentrated in the topsoil when deciduous wood vegetation persisted but leached quickly when agriculture started. In general, their study demonstrated that the SoilGen model can be used to simulate the effect of climate, vegetation and organisms on soil formation processes and properties.

An independent SoilGen model quality test was done by Sauer et al. (2012). Their study was aimed at testing how well soil development would be described by the SoilGen model. Against this background, observed soil properties from two chronosequences (12 soil profiles in total) in marine sediments of Southern Norway were compared with SoilGen simulated soil properties. Results from this study indicated that the SoilGen model simulated clay content and particle size distribution reasonably well. However, there was underestimation of OC, CEC, BS and pH and over estimation of clay depletion especially in the upper part of the soil profiles. The study concluded that the SoilGen model was capable of simulating soil development as a function of time with varying rates of success (Sauer et al., 2012). The overestimation of leaching in the topsoil was explained by the fact that formation of preferential flow structures (e.g. due to ripening) is unaccounted for by SoilGen.

Finke (2012) has applied SoilGen to model soil formation as a function of relief. The studied soil profiles were taken from 3 topographic positions of soil loess cover in the Zonian forest (Belgium). Input parameters to the model were the same for 3 topographic positions except for precipitation and evapotranspiration that had to be corrected for exposition and slope. Calcite dissolution rate, clay migration and physical weathering processes were first calibrated following procedures described in earlier sections. The model simulations after 15,000 years before present were confronted with field measurements of 3 topographic points. Results show that, the model was able to reproduce measured soil properties such as OC %, sand % and CEC. The model was also able to estimate the development of A, E and Bt horizons in response to sedimentation, bioturbation, physical weathering and clay migration soil forming processes. Base saturation and calcite content were however generally over estimated by the model most likely due to poor estimates of surplus precipitation, non-homogeneous initial calcite content and variations in initial bulk density (Finke, 2012).

2.4.1.1. Application domain: World Reference Base – Reference Soil groups. Table 4 shows which diagnostic horizons, properties and materials according to the World Reference Base (WRB; IUSS Working Group WRB, 2006) can be identified using the soil properties simulated by SoilGen2.16. As a consequence, Table 5 shows the application domain of SoilGen in simulating the genesis of typical features (excluding morphological features) of World Reference Base – Reference Soil groups (RSG). With the processes and chemistry currently described in SoilGen (i.e. clay migration, texture, CEC, BS, Al-chemistry), the millennium-scale genesis of typical features of 15 RSG can be simulated (Table 5). By extending the weathering and chemical systems of SoilGen (e.g. adding Fe and Si, mineralogy), the genesis of typical features of 9 more RSG can be simulated (Table 5). In total, SoilGen has a potential to simulate soil forming processes of up to 24 out of 32 RSG. Simulating the genesis of typical features of the remaining 8 RSG however remains a challenge due to the complexity of the processes involved. For example, simulation of Podzolisation process (Podzol RSG) requires describing the Al, Fe and OC complexation process, leaching of these complexes and the effects of soil micro- and mesofauna on humus breakdown (Table 5), which is currently difficult to implement in SoilGen. Technosols have a wide range of chemical and physical properties e.g. the effects of stoniness that currently cannot be simulated by SoilGen. Worthy to note here is that the model is not designed for application in acid sulphate soils as well as stony/gravely soils and thus RSG with such features may not be simulated.

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Table 4
Diagnostic horizons, properties and materials that can be inferred from SoilGen2.16 outputs. Morph = morphological properties; w.m. = weatherable minerals; min. = mineralogy; "waived" indicates those properties that matter for classification but are not essential. Petro* = petrocalcic, petroduric, petrogypsic and petroplinthic.

Diagnostic horizons		Diagnostic properties	
Inferable (waived)	Not inferable (cause)	Inferable (waived)	Not inferable (cause)
Anthric	Albic (color)	Abrupt textural change	Albeluvic tonguing (morph)
Argic	Anthraquic (morph)	Aridic properties (color)	Andic (min.)
Calcic	Cambic (color, structure)	Ferralic properties	Continuous hard rock
Cryic	Duric (Si)	Secondary carbonates	Geric (δpH, ECEC)
Folic	Ferralic (w.m.)		Gleyic color pattern (morph)
Gypsic	Ferric (color)		Reducing conditions (Fe, morph)
Histic	Fragic (slaking)		Stagnic color pattern (morph)
Irragric	Fulvic (min.)		Vertic (COLE, morph)
Mollic (color)	Hortic (P)		Vitric (min.)
Natric (structure)	Hydragric (Fe, Mn)		
Plaggic	Melanic (min.)	Diagnostic materials	
Salic	Nitic (Fe)	Not inferable (cause)	Not inferable (cause)
Umbric (color)	Petro*	Gypsiric material	Artefacts
	(Piso)plinthic (Fe, morph)	Mineral material	Colluvic material (morph)
	Sombric (color)	Organic material	Fluvic material (morph)
	Spodic (color, Fe)		Limnic material
	Takyric		Ornithogenic material (P)
	Terric (morph)		Sulphidic material (S)
	Thionic (S, min.)		Technic hard rock
	Vertic (morph)		Tephric material (min.)

Table 5
World Reference Base — Reference Soil Groups (RSG) that can (not) be simulated in SoilGen.

RSG-simulation, few limitations	Soil forming process[a]	Limitations (not simulated)
Crysols	Cryoturbation	Cryoturbation morphology
Solonetz	Solonization, solodization	Columnar structure
Solonchaks	Salinization	S and non-halite minerals
Chernozems	Melanization	Color
Kastanozem	Melanization, calcification	Color
Phaeozems	Melanization (argilluviation)	Color
Gypsisols	Calcification	Cementation
Calcisols	Calcification	Cementation
Alisols	Argilluviation, base cation leaching	Clay newformation
Acrisols	Argilluviation, ferrallitization	Clay newformation (simulation time)
Luvisols	Argilluviation, biological enrichment of base cations	Clay newformation
Lixisols	Argilluviation, biological enrichment of base cations	Clay newformation (simulation time)
Umbrisols	Melanization	
Arenosols	Very weak soil formation	
Regosols	Very weak soil formation	
RSG- simulation feasible		Processes/chemistry to include (limitations)
Anthrosols	Anthrosolization	P, Fe, Mn
Leptosols	Very weak soil formation	Soil production from hardrock
Fluvisols	Very weak soil formation	Physical ripening
Nitisols	Argilluviation, ferrallitization	Fe, weathering and clay newformation (structure, simulation time)
Ferralsols	Ferrallitization	Fe, Al, weathering and clay newformation (simulation time)
Planosols	Gleization, argilluviation	Fe, redox (ferrolysis)
Stagnosols	Gleization	Fe (stagnogley morphology)
Durisols	Silicification	Si (cementation)
Cambisols	Weak soil formation	Fe, weathering (structure)
RSG-simulation difficult		Causes
Histosols	Paludization	Peat growth and decomposition
Technosols		Artefacts, rock and highly varied mineralogy
Vertisols	Vertization	Argilloturbation process
Gleysols	Gleization	Gley morphology, Mn
Andosols	Andisolization	Allophane chemistry
Podzols	Podzolization	Al–Fe–OC complexation, migration and biobreakdown
Plinthosols	Gleization, podzolization	Plinthite morphology and consistence
Albeluvisols	Argilluviation	Albeluvic tonguing

[a] Terminology of Bockheim and Gennadiyev (2000).

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2.4.2. *Landscape scale applications*

The potential application of the SoilGen model at landscape scale has been demonstrated in recent studies by Zwertvaegher et al. (2013) and Finke et al. (2014). In Zwertvaegher et al. (2013), SoilGen was applied to different point locations (96 profiles) distributed over an area of 584 km^2 in sandy Flanders (Belgium) to reconstruct soil characteristics such as texture, bulk density, OC %, calcite and pH. Calibration of calcite dissolution rate was done as discussed earlier (section 2.4.2). The predicted variables were confronted with measurements and generally showed good agreement. Predicted point soil characteristics were then used to produce full cover soil maps at a given period of time using regression kriging techniques. The soil map produced was used in combination with hydrological model, digital elevation model (DEM) and land evaluation model for application in landscape reconstruction and archeological land evaluation.

Finke et al. (2014) have applied the SoilGen model to simulate variation of soil characteristics (e.g. OC, calcite content and clay content) and soil horizons at landscape scale in the presence and absence of tree uprootings. In their study, they formulated a probabilistic approach to predict the occurrence of tree uprooting in a certain year at pedon scale. Simulations were done at 108 locations for two scenarios: one in which soil formation occurs without the influence of tree uprootings and one with the influence of tree uprootings. To compare with the observed horizons, simulated soil characteristics at present year were converted to horizon thicknesses following a protocol developed using measured and simulated soil data (Finke et al., 2014). Regression kriging was then used to produce spatial soil–landscape relationship using an approach similar to that of Vanwalleghem et al. (2010). Their findings indicate that including tree uprooting events in the SoilGen model better explains spatial patterns of horizon thicknesses. In addition, the model simulations showed that the relation between the starting depth of some horizons (e.g. Bt) and terrain properties was lost due to the homogenizing effect of treefalls. This was consistent with the observations in the field by Vanwalleghem et al. (2010).

2.4.3. *SoilGen model limitations*

The aforementioned studies clearly demonstrate the potential field applications of SoilGen both at pedon scale and at landscape scale. However, results from these studies have also reported some cases of major discrepancies between model predictions and measurements. These discrepancies can be partly attributed to (1) incomplete process descriptions, (2) incorrect estimates of initial data inputs and (3) incorrect values of variables that describe boundary conditions (Finke, 2012). Furthermore, heterogeneity within the soil profile is only partly captured as the model assumes a homogeneous initial mineralogical composition. There are also issues of process simplifications such as constant volume of each compartment with time.

According to Vanwalleghem et al. (2013), the major limitation of the SoilGen model especially for application at landscape scale is its inability to take into account spatial patterns and links between individual profiles. At landscape scale, data requirement and simulation time also increase. In addition, verification of pedon-landscape linked models becomes very difficult if not impossible especially when dealing with human-affected landscapes because the land use history is often imprecisely known at the level of model input parameters.

2.4.4. *Future priorities*

In its current state, the SoilGen chemical weathering module describes only four primary minerals (Anorthite, Chlorite, Microcline, Albite) as major pools for Ca, Mg, K and Na, respectively. This means that the fate of a wide range of primary minerals and elements may not be simulated. In addition, formation of major secondary minerals are not taken into account in SoilGen weathering and chemical systems. Formation and presence of these secondary clay minerals is important as they influence CEC. CEC together with clay content and OC are used in the SoilGen model (clay migration module) to simulate the amount of dispersible clay. Therefore there is need to explore the possibility of extending the description of SoilGen chemical weathering module such that it can accommodate the weathering of more primary minerals, release of more elements as well as the formation of major secondary minerals.

SoilGen chemical module also needs to be extended to allow simulation of more chemical species such as Si and Fe. These species have pronounced effects on most soil forming processes and soil properties. For example Si in form of phytoliths has been shown to influence the decomposition rates of organic carbon while Fe may cause cementation and influences the composition of the exchange complex. If Si, Fe and Al fate is simulated, weathering indices can be calculated as well, which enlarges the possibility to compare model results with field studies reported in literature. The chemical module therefore needs to be developed in such a way that it is flexible and allows interactions among chemical elements. Well-developed weathering and chemical systems will probably improve simulations of soil chemical properties such as BS, CEC and pH.

Furthermore, the interaction between the soil and the vegetation in SoilGen is currently described through ion uptake and annual litter input. However, the changes in the annual litter input in response to soil conditions such as soil moisture and temperature are not captured. To capture these interactions and feedbacks, there is need to implement the concepts of soil-vegetation interactions usually described in vegetation models.

Inclusion of the above processes will improve the description of the weathering and chemical systems in the SoilGen model. In addition, these inclusions will enhance the SoilGen model flexibility so that it can be applied to different parent materials and simulation of genesis of typical features of at least half of the WRB-RSG. Capturing interactions and feedbacks between the soil and vegetation system will also enhance the sensitivity of the SoilGen model to global change.

3. Soil genesis in landscape evolution models

3.1. *Current capabilities of landscape evolution models*

Landscape evolution models are those in which soil production and soil redistribution over time is simulated at a landscape scale. In contrast to pedon scale models which are mainly based on pedology and geochemistry, landscape evolution models are mainly based on geomorphology and soil is simulated as a single layer of regolith (Minasny et al., 2008). Major soil forming processes considered include physical weathering, chemical weathering, erosion and deposition (Minasny and McBratney, 2001). These models (e.g. Dietrich et al., 1995; Minasny and McBratney, 1999, 2006) and notably the LAPSUS-model by Schoorl et al., 2002 and the MILESD-model by Vanwalleghem et al. (2013) have successfully been applied to simulate soil thickness over time as influenced by weathering and erosion processes. The limitations of these approaches are that, they consider only the solid phase of the soil and thus the impact of water flow on soil formation is not accounted for. This means that such models cannot be used to simulate soil formation under varying climate and land use (Samouëlian and Cornu, 2008; Samouëlian et al., 2012). In addition these approaches assume a closed system within the landscape such that, apart from soil production by weathering there is no soil either lost from the

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landscape or brought into the landscape from areas outside the model, e.g. by loess deposition or alluvial inputs, thus simplifying reality. There is also no clear horizonation of the soil when applying these models (Samouëlian and Cornu, 2008). According to Vanwalleghem et al. (2013) most landscape models do not explicitly consider soil forming processes and thus observed differences may only result from sediment sorting by erosion and deposition processes. Practically, it is also very difficult to verify these models under field conditions.

To address some of these limitations, there is a need to work towards an integrated system (Vanwalleghem et al., 2013) in which fully tested pedon scale models are integrated or linked to landscape models, thus producing soilscape genesis models.

3.2. Towards modeling of soilscape genesis

Probably the simplest case of soilscape development modeling is when soil redistribution across the landscape is negligible and water fluxes are mainly vertical. In that case, spatially distributed modeling with a pedon-scale model in combination with geostatistical mapping methods will suffice to produce maps of soil properties for desired points in time. Such approach has shown promising results. Zwertvaegher et al. (2013) did multiple point simulations with SoilGen in a relatively flat cover sand area for the period from the Younger Dryas up till recently, and interpolated pedon-scale results (e.g., base saturation in the topsoil) to full coverage maps for desired points in time by a regression kriging technique. Finke et al. (2014) did likewise in a forest-covered landscape without much erosion in loess parent material.

When soil redistribution through erosion and sedimentation processes occurs, but water fluxes are still mainly vertical, a 1-D pedon soil genesis model may be linked to landscape evolution models. The pedon model runs for several geographic position in the landscape and communicates with the landscape model at meaningful time intervals. In this case, the landscape evolution model provides boundary inputs to the pedon model: the amount of soil material lost by erosion or added by sedimentation at the surface boundary during a time interval. SoilGen is able to handle surface loss by erosion or addition of soil material of known composition. This requires that the transported material is characterized in terms of all the soil properties that are used in the pedon model, such as texture, OC percentage and element composition. The pedon model can return the topsoil composition to the landscape model to update the erodibility and infiltrability and their spatial distributions. Such model linkage is feasible, but the large computing time probably limits the amount of pedon scale models that can be linked to the landscape model. As in case of the spatially distributed modeling, geostatistics can be of value to obtain complete coverage of the landscape with pedogenetic data. When erosion processes are known to be dominant over soil formation processes in a particular period, a time-split approach as proposed by Sommer et al. (2008) may be applied to use either a distributed soil formation model or a soil redistribution model in such period, thus saving computing effort.

The most complex case is when soil redistribution takes place and water flow is not strictly vertical. Ideally, in this case a 3-D soilscape model is developed that integrates surface soil redistribution processes, a 3-D water and solute transport model and additional model components that cover the soil formation processes. Such model is not known to exist today, and is expected to be computationally demanding.

A general problem with modeling of soilscape genesis is that various boundary inputs must be assessed for all positions in the landscape and also over time, in particular this concerns the type of vegetation and its coverage and agricultural land use. Such reconstructions are highly complex and the resulting boundary inputs are associated with uncertainty.

In summary, the major issues to be solved in the modeling of soilscape genesis are computation time and data demand. These issues may render simplification of some process descriptions unavoidable. Part of the solution points to the development of complete and tested pedon scale models that are at a later stage simplified and tuned to reproduce the detailed pedon models. For such testing, there is need for high quality profile datasets (e.g. chronosequences, climosequences and toposequences).

4. Conclusions

Models for soil evolution are increasingly becoming invaluable tools to provide soil information required for hydrological, land evaluation, biogeochemical and global change studies. Although still limited, such models are progressively being developed. We demonstrate here that the SoilGen model is one of such models with capabilities to simulate soil formation over multi-millennia time scale. Simple calibration approaches have been developed and used to calibrate the SoilGen model. The model has undergone extensive field testing and satisfactory results at both pedon and landscape scales have been reported. Its ability to take into account complex physical, geochemical and biological processes coupled with water flow makes it such a unique and versatile soil evolution model. However there is still need to further develop it for application in different environmental scenarios and for a larger variety in parent materials. Particularly the chemical and weathering systems need to be extended in a flexible way.

Landscape evolution models are valuable to simulate soil production and distribution over time at landscape scale. The major drawback of these models is that only soil solid phases are considered and limited number of soil forming processes (i.e. only physical/chemical weathering, erosion and deposition) are considered. Working towards an integrated system of pedon and landscape models presents a better approach to improve modeling of landscape evolution. However, increased data requirement and computation time remain a major challenge.

There is a critical need for high quality chronosequence, climosequence and toposequence profile datasets. This type of dataset would surely provide a good test for soil evolution models. Pedologists also need to strengthen links with other disciplines such as palaeopedologists, Critical Zone and climate research communities. Such links will undoubtedly facilitate better understanding of soil formation through collaboration and sharing of quality data, technology and experiences.

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