

The Uncalm Development of Proglacial Soils in the European Alps Since 1850

18

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Abstract

Glaciers in the Alps and other mountain regions are widely retreating. This contribution focusses on the soils that are forming in the proglacial areas. These soils are important because of the hydrological and ecological effect they will have in future glacierless valleys. A geographical approach is taken that attempts to explain differences in rates of soil formation between proglacial valleys. Through a comparison of published soil chronosequences of European proglacial areas, it is found that age is the most important factor determining rates of soil development—even where morphodynamics are strong. Nonetheless, the effect of geomorphic activity and the effect of vegetation succession have been clearly observed in several studies. The combination of all factors forces us to acknowledge a complex model of soil formation in alpine proglacial valley that among

others highlights the heterogenous and dynamic nature of morphodynamics. This model invites us to fill in some blanks in our understanding and suggests that with a larger number of proglacial soil development studies, we may be able to provide pan-alpine information on soils in proglacial areas. This is of importance, for instance, when establishing pan-alpine carbon budgets.

Keywords

Soil development · Proglacial area · Soil types
Chronosequence · Morphodynamics

18.1 Introduction

As poster children of climate change, images of retreating glaciers are ubiquitous in the public domain. Repeat visitors to alpine valleys experience these changes themselves when looking out to glacial remains over usually large expanses of glacial till and side moraines that are coarse, badly sorted, sometimes unstable or unsettled, and above all recent. These are images of lost functionality. Less glacial mass means less melting in summer and hence less water in large continental rivers (Singh and Bengtsson 2005), and less glacial mass can also mean less

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mountain tourism, not only by mountaineers who like to traverse glaciers, but also by tourists who like to look at glaciers from safe ground (Beniston 2003; Carey 2010). The melting process itself can cause the formation and possibly catastrophic failure of glacial dams which is an important natural hazard in mountain regions (Huggel et al. 2002; Richardson and Reynolds 2000). One is justified in asking whether there is any functional gain to offset these losses. The development of soils in the ‘new land’ in front of retreating glaciers is one potential functional gain and the topic of this chapter.

Soils in proglacial environments are important. First, the properties of soils formed in the usually thin deposits covering bedrock play a large role in the hydrological behaviour of proglacial valleys. Where soils are better developed—with more weathered rocks, a larger clay fraction, better soil structure and more organic matter—they can better retain water during the melting season and after rainstorms (e.g. Wösten et al. 1999). This means that they are better able to dampen peak outflows, and that they are better able to continue to provide water to downstream areas during dry periods. The latter is particularly important when contemplating a future in which most alpine valleys will no longer contain glaciers (e.g. Haeberli et al. 2007), and hence can no longer benefit from a steady flow of glacial meltwater in summers (Xu et al. 2009).

A second important functionality of proglacial soils is the fact that their (pedo-)diversity is the template for biodiversity. If developing soils in proglacial valleys substantially increase their variation over time, they will be better able to support proglacial floral and (micro-)faunal diversity (Khaziev 2011). Over a timescale of decades, such an increase in proglacial biodiversity could become more important than the expected loss in downstream riverine biodiversity due to a larger proportion of cold glacial meltwater (Jacobsen et al. 2012).

In the context of this importance of proglacial soils, the objective of this chapter is to review current knowledge about soil development in proglacial areas, with particular emphasis on the relation between soils and morphodynamics.

Geographical focus is on the European Alps, and temporal focus is on the development of soils since the end of the Little Ice Age (LIA), around 1850. In the European Alps, there is usually good control on the retreat history of glaciers since this time (Chaps. 2 and 3), which is a prerequisite for chronosequence studies.

18.2 Proglacial Soil Development Studies in the European Alps

Most studies of soil development and ecological succession in proglacial valleys have focussed on these valleys, because they present beautiful natural experiments where the effect of time on soil development can be well studied. Site selection has therefore prioritised valleys where glacial retreat has been uninterrupted and gradual, and where effects of morphodynamics and other disturbing factors are perceived to be of minimal importance. From these studies, important conclusions have been drawn about the rates of soil development in alpine climates. However, the prioritised valleys represent end-members of the complete set of proglacial valleys. This is because in many proglacial valleys, a wide range of hillslope processes affect the valley (cf. Chaps. 8, 9, 10 and 11), glaciers have not retreated in an uninterrupted manner, parent material is not uniform glacial till, and developing vegetation (Chap. 19) exerts a control on soil development that modulates the influence of time. Recent studies have started to elucidate these additional effects, so that ultimately a more complete picture of soil development in proglacial valleys is emerging.

The end point of soil development in most alpine valleys of intrusive or strongly metamorphic lithology is a (usually skeletal) podzol—a soil type with acidic topsoil characterised by the e- and illuviation of organic matter associated with Fe- and Al-sesquioxides (WRB 2015, Fig. 18.1c). Exceptions have mainly been reported from less common lithologies and drier intra-alpine climates (D’Amico et al. 2014a, b, 2015). However, the podzol as a developmental endpoint is often only reached after about

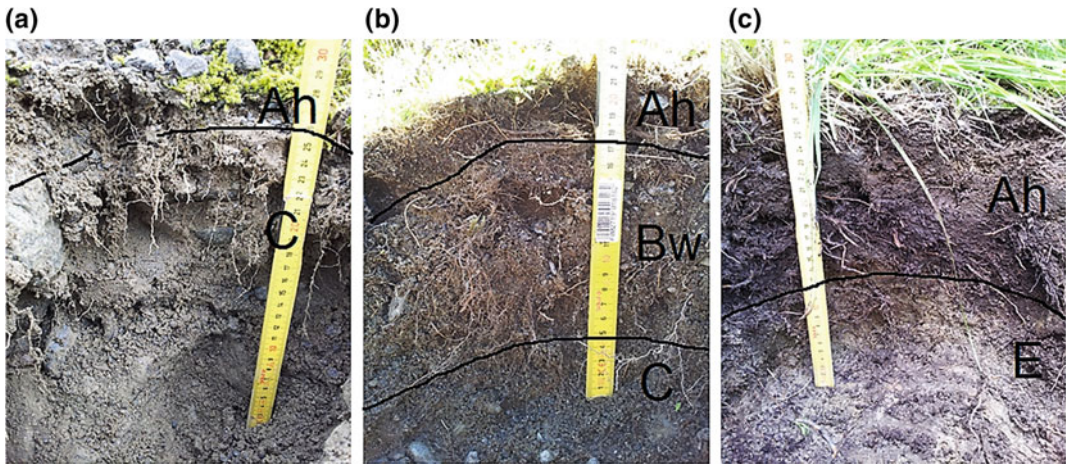


Fig. 18.1 Examples of proglacial soils adapted from Temme et al. 2016. **a** Skeletic regosol. **b** Skeletic cambisol. **c** Haplic podzol. The first two soils are from

within a proglacial area, the third is from outside a proglacial area and is older than the LIA

1000 years (Egli et al. 2001; Zech and Wilcke 1977), although some of the oldest post-LIA soils in proglacial valleys in Italy (between 190 and 250 years old) are also podzols (D'Amico et al. 2014a, b).

Typically, the oldest post-LIA proglacial soils in the European Alps are less than 180 years old and hence less developed than that. The most common soils are skeletal, hyperskeletal or humiskeletal leptosols and regosols. Below, I will review the pedological work done in several proglacial valleys in the Alps (Fig. 18.2), starting with more traditional chronosequence work before broadening the field to include studies that focus on a wider range of soil forming factors, including morphodynamics. Inevitably, I am not doing justice to the full breadth of work in alpine proglacial valleys. Given the soil-geographical approach of this chapter, studies that focus purely on soil-related processes outside of the geographical context of soil forming factors are not discussed in detail. This includes much work focussing on the development of microbial soil fauna with time (e.g. Duc et al. 2009; Nicol et al. 2005; Philippot et al. 2011; Schmalenberger and Noll 2009; Schurig et al. 2013; Sigler and Zeyer 2002; Tschërko et al. 2003). In addition, I consider it likely that my literature search has missed

some of soil chronosequences explored in the context of ecological research questions.

18.2.1 Morteratsch Glacier

The proglacial valley of the Morteratsch glacier (Fig. 18.2) is possibly the best-studied proglacial valley in the Alps, mainly due to many studies by scientists from the University of Zürich. Building on early ecological work focussed on the time-dependent development of vegetation (Burga 1999; Stöcklin and Bäumler 1996), Egli et al. (2006b) used a detailed soil map of the Morteratsch proglacial area to derive chronosequences for soil types occurring in the valley. Soil types that were observed in this study were mainly lepto- and regosols, with occasionally cambisols in the older parts of the proglacial valley. In addition to soil age, there were indications that soil types varied between landforms and between classes of slope steepness (Egli et al. 2006b). However, this was not tested statistically at the time, and the method to map soils based on 47 soil pits might have partially introduced some of these relations. In an accompanying publication, Egli et al. (2006a) used the relations between ages, landforms and relative occupancy by



Fig. 18.2 Locations of some proglacial soil chronosequence studies, and location in Europe (inset)

different soil types to simulate a future soil map of the Morteratsch valley after continued retreat of the Morteratsch glacier. The topography of parts of the valley that were still covered by the glacier at the time of writing was simulated based on splines (Jürgens and Biegger 2006).

Later investigations of the Zürich group on soils in the Morteratsch forefield focussed on the weathering and soil-forming processes in more detail (Mavris et al. 2010). Despite the only weak topographic variation in the proglacial valley, it was found that soils on (slightly) north- or polar-facing slopes were better weathered and had higher rates of smectite formation than soils on south- or equator-facing slopes (Egli et al. 2011). It was hypothesised that the availability of water for weathering explained the differences, even in these cold environments where weathering was expected to be temperature-limited. In the alpine proglacial environment, water availability is higher on north-facing surfaces because there is less evaporation. This water-availability hypothesis was later strengthened and detailed by results from the Altai Mountains in Siberia (Egli et al. 2015) and from the Front Range of the Rocky Mountains in Colorado (Langston et al. 2015). Langston et al. (2015) suggested for their study area that the increase in water availability

on polar-facing slopes could also be explained by the fact that snow there often accumulates throughout winter and melts only at the end, providing the soil with a stronger pulse of melt-water than on equator-facing slopes, where melting can occur more frequently, but then results in smaller pulses of water in the soil. This mechanism may be valid for the European Alps as well.

A more geographical approach to soil variation in the Morteratsch valley was recently taken by Temme and Lange (2014), who studied soils at an additional 50 point locations in the valley. The focus of this study was on the quantification of relations between soil properties on the one hand, and soil age and terrain parameters on the other hand. In this sense, it mirrored to some extent the first studies by Egli et al. (2006b), who studied this relation for soil type rather than soil properties. Soil age was found to explain about 60% of the variation in pH, and 40% of the variation in the depth of soil formation (A and B horizons) and the vegetation cover. The effect of morphodynamics (based on terrain parameters measured in the field and derived from a 30-m resolution Digital Elevation Model) was significant but less important than the effect of time. Linear regression models of the soil properties

based on age, slope steepness, curvature and insolation explained between 80% (pH) and 30% (stoniness) of variation. Based on these results and qualitative field observations, it was hypothesised that the effect of morphodynamics might be best quantified at smaller spatial resolution than 30 m. Many of the small landscape features that appeared to drive soil variation were smaller than this scale.

18.2.2 Forno and Tschierva Glaciers

The Forno and Tschierva glaciers are geographically close to the Morteratsch glacier (Fig. 18.2). This allowed Temme and Lange (2014) and Temme et al. (2015) to consider them climatologically and lithologically relatively similar to that valley. The three valleys differed in terms of glacial retreat history, which was regular in the Forno and Morteratsch valleys, but irregular in the Tschierva valley—and in terms of hillslope effects on the proglacial plain, these were considered absent in the Morteratsch, weak in the Tschierva and strong in the Forno valley. Hence, soil development in the Forno and Tschierva proglacial valleys was expected to be a less strong function of age than in the Morteratsch proglacial valley. This was indeed the case: correlations between soil properties and soil age were weaker in these two valleys (Temme and Lange 2014). However, landscape properties (again resolved at 30 m) did not have a stronger effect than in the Morteratsch valley, resulting in overall less variation in soil properties explained by regression models in the Forno and Tschierva valleys.

The diversity of soil properties, expressed as the coefficient of variation, was found to increase with soil age in the Morteratsch valley, but decrease with age in the Forno and Tschierva valleys (Temme et al. 2015). It was hypothesised that the increase in diversity resulted from positive feedbacks on soil development that amplify small differences in parent material or topographic position, and that the decrease in diversity resulted from hillslope processes that have affected older soils somewhat equally, and more than younger soils.

18.2.3 Damma Glacier

Investigations of soils in the Damma Glacier forefield (Fig. 18.2) have a long history, particularly because of work in the context of the Biglink project (Bernasconi et al. 2008). Much of the work has focussed on establishing the soil microbial and nutrient development with increasing soil age. This microbial development of proglacial soil is strongly interdependent with the development of other soil properties. Overall, soil pH (decreasing), cation exchange capacity, biomass and bacterial and fungal communities (all increasing) changed with soil age (Bernasconi et al. 2011).

The increase in soil carbon is accompanied by a stronger increase in C throughput (Guelland et al. 2013), changing the soil system from one dominated by accumulation to one with high throughput within the approximately 100 years of chronosequence studied. Much of the accumulation of soil carbon was found to be in the form of microbial cell-envelopes (Schurig et al. 2013), highlighting the importance of microbial communities in soil C-dynamics. Overall C accumulation was not only a function of soil age, and a clear negative effect of colder decades on accumulation rates (and on Net Primary Production) was observed (Smittenberg et al. 2012). Also rates of litter mineralisation were not a function of soil age—the main driver appeared to be soil wetness, with drier locations experiencing slower litter breakdown (Guelland et al. 2013).

Vegetation on the young developing soils in the Damma proglacial area was both N- and P-limited. Nitrogen was mainly delivered through atmospheric deposition and rock funnelling, not through N₂ fixing (Göransson et al. 2016). Already in young soils, stocks of S are mainly in the form of organic complexes as opposed to inorganic S (Prietzel et al. 2013). This too highlights the importance of microbial communities: these are needed to degrade organic S complexes to provide S to growing plants. Microbial communities along the chronosequence contained more mycorrhizal fungi at younger age and were dominated by bacteria and other fungi at older age (Welc et al. 2012).

An expected shift in older, more acidic and organic rich soils from bacteria to fungi was not observed within the chronosequence, and must therefore occur later in the development of soils into Podzols.

18.2.4 Gepatsch Glacier

Studies in the forefield of the Gepatschferner in the west of Austria (Fig. 18.2) have focussed on the morphodynamics related to glacial retreat (Heckmann et al. 2012; Chaps. 1, 5, 7, 9, 11, 13, 17). The fact that the area is suited for this purpose already suggests that the Gepatsch proglacial area is an area where soil development cannot be expected to be a clear function of time.

First, the Gepatschferner has not retreated uninterruptedly. It has re-advanced slightly between 1970 and 1997 (Hartl 2010). Second, in contrast to the previously discussed valleys where bedrock was granite, the bedrock in the Gepatsch valley is gneiss with a small fraction of pyrite (Vavtar 1981). Thirdly and most importantly, the proglacial area is affected by fluvial redistribution, undercutting and degrading moraines, and debris flows from surrounding slopes (cf. Chap. 11). The activity of the proglacial stream, the Fagge, is strongly variable in time and affects a substantial fraction of the proglacial area (Morche et al. 2012; Morche et al. 2014; Baewert and Morche 2014; Chap. 13). Moraine degradation and debris flows were quantified using repeated Lidar data and also affect a substantial fraction of the proglacial area (Haas et al. 2012; Chaps. 11 and 17). These morphodynamic processes have a different spatial signature: the effect of fluvial redistribution runs largely parallel to the valley axis, whereas the effect of collapses and debris flows is roughly parallel to the slopes (i.e. perpendicular to the valley axis) and concentrated in the most narrow reach. As a result, their influence on soil–age relations is not easily predicted.

Soils in the Gepatsch proglacial area were studied by Temme et al. (2016), with the objective of leveraging the detailed morphodynamic information to clarify the joint effects of age and

morphodynamics on young, developing soils. The sampling design (for 97 locations) ensured that the effects of age and morphodynamics could both be reliably quantified. The main outcome was that despite the morphodynamic activity, age remained a main control on soil properties at the level of the entire proglacial valley. However, the effect of morphodynamics could be much better studied with the detailed digital elevation models (DEMs) available from the morphodynamic studies, than had been the case for earlier chronosequence studies.

In fact, the correlation between a range of soil properties and some morphometric indicators exhibited a clear scale-dependence. This allowed an assessment of the morphodynamic processes that affect soil properties. It was shown that correlations were usually low at the previously used 30-m resolution (e.g. Temme and Lange 2014), proving that morphodynamic processes typically affect soils and soil patterns at smaller scale than 30 m. Profile curvature, which indicates whether a position is likely to experience erosion or deposition, was strongly correlated with pH and the combined silt and clay fraction at resolutions ranging from 1 to about 5 m. Eroding soils had higher pH values and lower amounts of silt and clay. The stream power index, which indicates to which extent a position is exposed to fluvial activity, was strongly correlated with soil properties at resolution ranging up to 25 m. Soils in floodplains had higher pH values and rooting depths, but lower amounts of silt and clay. The main point taken from the study for our purposes here should be that soil development in places where morphodynamics play a substantial role is far from calm and undisturbed—but that morphodynamic effects can be well quantified with detailed altitude data.

18.2.5 Lys and Verra Grande Glaciers

Building on larger-scale soil surveys in the Aosta Valley (D'Amico et al. 2014a), scientists from the University of Turin studied two proglacial valleys that are of interest because of their widely different lithologies: the proglacial valleys of the

Lys and Verra Grande glaciers (Fig. 18.2; D'Amico et al. 2014a, b, 2015). The Lys glacier overlies granitic gneiss and paragneiss bedrock with minor mafic and ultramafic intrusions, whereas the Verra Grande glacier mostly overlies serpentinite bedrock. Retreat histories are similar in the sense that both glaciers retreated from a position closely upslope of the LIA maximum moraine around 1860 (Carnielli 2005; Citterio et al. 2007)—however, the LIA maximum extent itself (and soils developed on it) of the Verra Grande glacier is probably a few hundred years older than 1850 (D'Amico et al. 2015). Compared to the other proglacial valleys reviewed here, the Verra Grande and Lys valleys are also the only two south of the main alpine arc, and the only two that are generally facing south.

Soil development with time is faster in the gneiss-based Lys proglacial valley than in the serpentinite-based Verra Grande proglacial valley (D'Amico et al. 2015). Serpentinite-based soils are generally seen to reduce plant productivity (Alexander et al. 2007). Perhaps because of this limitation of plant productivity, the effect of ultimate colonisation by grasses and larch shrubs was clearly seen in soil properties. Grass and later shrub colonisation of soils in the Verra Grande proglacial area clearly accelerated soil development rates, although these remained lower on serpentinite till than those in the Lys proglacial valley and in parts of the Verra Grande proglacial valley where the parent material was less pure serpentinite. Also in the Lys valley, the effect of vegetation colonisation was clear. In this case, subalpine larch and rhododendron vegetation accelerated soil formation to the extent that 60-year-old soils displayed bleached E-horizons (D'Amico et al. 2014a). The authors argued that this vegetation type, rather than climatic factors, explains the exceptionally fast soil formation relative to other study areas.

The limitations placed on vegetation succession on serpentinite-dominated till were argued to enhance the vulnerability of these areas to environmental change (D'Amico et al. 2016). In this context, it is good to realise that although serpentinite is common in orogenic belts, it is much less so than granitic or gneiss bedrock, on

which vegetation establishment and soil development are much faster. In the European Alps, mafic and ultramafic rocks are mainly limited to the Swiss and western Italian Alps.

18.3 Soil Development as a Function of Time

When comparing the effect of time on soil properties between study sites (Table 18.1), it is necessary to choose a functional form for the soil–time relation in each site. In most cases, rates of change have been found to increase after a few years (or at least from when vegetation is established, D'Amico et al. 2015) and reach a maximum for ages between 100 and 1000 years. Rates of change then drop to low long-term steady-state values (e.g. Egli et al. 2001). This type of development is functionally akin to the humped weathering model that explains how bedrock weathers into soil (Burke et al. 2007). Exceptions exist, such as the slow start of development on serpentinite parent material (D'Amico et al. 2016). During the slow start, accelerating soil development would be well described with an exponential model. Where the maximum value of a development indicator is reached, such as for vegetation cover, and soil development slows down, a logistic growth function would be appropriate. Here, to allow objective comparison and for ease of reporting, the observations provided with the various studies discussed above have all been linearly regressed to age.

As mentioned before, the Verra Grande glacier proglacial area, where serpentinite parent material slows down vegetation establishment, displays some of the lowest rates of development. However, there appears to be also significant variation in rates of development between proglacial areas of the same lithology. Although this may to some extent be due to uncertainty in the estimation of the rates, it is also likely that climatic differences between proglacial areas (for instance, between Lys and Gepatsch) and different morphodynamic settings (for instance, between Morteratsch, Forno and Tschieriva)

Table 18.1 Comparison of annual rates of change in various soil properties between the proglacial valleys

Annual rate of change in soil properties					
Location	Lithology	pH (-)	Topsoil OM (M%)	Vegetation cover (%)	Depth of soil formation (cm)
Morteratsch (Temme and Lange 2014)	Granite	-0.017	–	0.53	0.021
Forno (Temme and Lange 2014)	Granite	-0.008	–	0.5	0.061
Tschierva (Temme and Lange 2014)	Granite	-0.014	–	no relation	0.014
Damma (Dümig et al. 2011)	Granite	-0.007	0.034 ^b	–	0.027
Lys (D'Amico et al. 2014)	Gneiss	-0.0078	0.025 ^b	>0.59	0.07
Gepatsch (Temme et al. 2016)	Gneiss	-0.0035 ^a	0.105	–	–
Verra Grande (D'Amico et al. 2015)	Serpentinite	-0.0075	0.009 ^b	0.31	~0.03

Rates are calculated using linear regression where no intercept was imposed

^aFor soils older than 20 years. Younger soils experienced a pH rise that was assumed related to pyrite weathering in fresh sediment

^bObtained from SOC values using the Van Bemmelen factor (SOC = 0.58 SOM)

cause these differences. It is attractive to contemplate a meta-analysis of development rates at the point-scale rather than the scale of the proglacial area. This could allow a separation of the effect of morphodynamics from the effect of climate, where variation within areas would be mainly caused by morphodynamics and micro-topographical differences, and variation between areas by climate. However, a much larger data set of proglacial chronosequences will be needed for this purpose.

18.4 A Complex Model of Soil Development in Proglacial Areas

Beyond the effect of age, which clearly appears to differ between sites, a complex model of proglacial soil development emerges from the various studies reviewed above (Fig. 18.3). In this model, proglacial soil development is neither linear, nor monotonous or calm (cf. Bardgett et al. 2005; Sommer et al. 2008). The calmest case is a proglacial area where moraines protect the valley from hillslope influences and

geomorphic activity plays a negligible role, but even here, minor or major differences in the glacial till parent material (Fig. 18.3A) will get amplified over time as initial soil formation, dominated by positive feedbacks, speeds up (D'Amico et al. 2016; Temme et al. 2015).

Moreover, since vegetation and associated soil (micro-)fauna develops strongly nonlinearly over time through various successional stages, vegetation influence on soil development is also nonlinear (either speeding up with time, or reaching a maximum and then decreasing). This can cause further divergence in properties (Fig. 18.3H; D'Amico et al. 2014a, b).

Additionally, in most proglacial areas, there are one or more morphodynamic and geomorphic complicating factors. The most important one is where erosion rates in steep proglacial valleys allow neither soil development nor vegetation establishment. In such sections, the proglacial valley appears headed for a pure bedrock valley floor. The eventual or original absence of till where bedrock crops out (Fig. 18.3D), and the effect of eroding and collapsing moraines (Fig. 18.3B) and debris flow from hillslopes overlying the proglacial area (Fig. 18.3C), all also

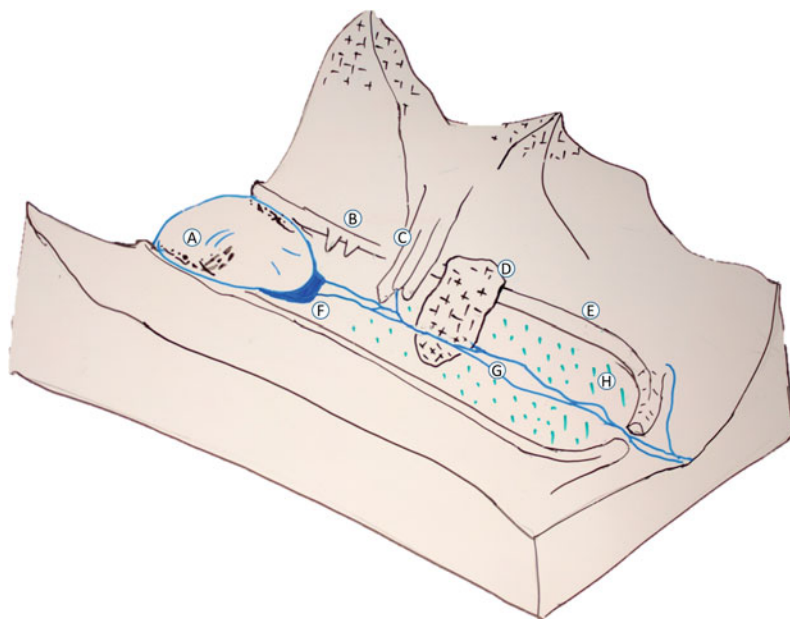


Fig. 18.3 Sketch of a proglacial valley. Factors that can affect the time-dependent development of soils in proglacial areas are indicated with characters. A indicates the provision of heterogeneous sub- and supraglacial till to the proglacial area. B indicates the degradation of lateral moraines. C indicates hillslope processes, including debris flows, from surrounding hillslopes. D indicates the

absence of till or moraine material where bedrock surfaces. E indicates undisturbed moraine, decoupling the proglacial area from external sediment fluxes. F indicates the effect of glacial lakes, and G indicates fluvial redistribution. H indicates the effect of vegetation transitions and patterning

affect soil formation. The mechanism by which this effect occurs is often the burial of soils under material provided by moraines or hillslopes. This has a negative effect on the level of soil development if the material is provided from fresh, unweathered sources (such as steep-side moraines), but can have a positive effect on development if the material is provided from hillslopes which have often been exposed for much longer than the proglacial area. Both of these examples have been observed in the European Alps (Temme et al. 2015). Reworking of material during consecutive episodes of erosion and deposition complicates this process both in the source zones and in the proglacial area. The imperfect sedimentary connectivity of the morphodynamics of hillslope and fluvial processes causes varying residence times of paraglacial sediment on its way to the proglacial area and ultimately further downstream (Heckmann et al.

2012, Knight and Harrison 2014; Chaps. 15, 16 and 17).

Buried palaeosols are sometimes found in proglacial areas. Their persistence indicates that burial has been fast relative to soil formation speeds. Examples come from the Austrian Alps (Mahaney et al. 2011) and from British Columbia (Karlstrom and Osborn 1992) and Spitsbergen (Kabala and Zapart 2009). In Austria, the buried soils were found under LIA moraines and hence older than the LIA. These palaeosols had a convoluted character, indicating either cryoturbation or pushing by moraines during the LIA (Mahaney et al. 2011).

Soil development is also affected by fluvial morphodynamics (Fig. 18.3G; Chaps. 12 and 13). Incision, lateral erosion and deposition all affect soil properties. The fluvial effect is more substantial where proglacial streams are multi-channel and affect a relatively wide floodplain in

the proglacial valley. This is often the case in Little Ice Age proglacial areas because fluxes are strongly seasonal with maxima during the melting season, and there is ample presence of unconsolidated sediment (Morche et al. 2014). The alternative, a single-channel stream with stable banks, would affect soils much less, but is more typical for mature catchments with vegetated banks and less seasonal flux.

18.5 Implications

The main implication of this more complex model of proglacial soil evolution is that spatial upscaling from chronosequences and chronofunctions is not easily possible. To answer questions about the global, or even the European alpine carbon budget of proglacial areas, for instance, it is necessary to assess how important each complicating factor is in each proglacial area, or in groups of proglacial areas, and then account for the effect of these factors on the budget. At the same time, it appears that the process knowledge is available that would allow for such an assessment. From this, it appears that data sets that are required and sufficient for a carbon budget of proglacial areas of the European Alps would include the extent of proglacial areas, the extent of bedrock in proglacial areas, retreat histories and retreat predictions for glaciers, geological maps, a digital elevation model, current and predicted vegetation maps and chronofunctions for the rate of below-ground organic matter accumulation as a function of location, vegetation and parent material. Although this is a long list, most of these data are currently available and others can be relatively easily produced. Probably the most difficult aspect remains accounting for the complex effect of active morphodynamics on soil development. Elucidating this morphodynamic effect at appropriate spatial scales should therefore be part of the future research agenda, along with an increased understanding of how different parent materials and climatic settings determine the variation in chronofunctions.

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