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Climate change impacts on the Alpine ecosystem: an overview with focus on the soil – a review

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ABSTRACT: The Alpine ecosystem is very sensitive to climatic changes, which have an influence on glaciers, snow, vegetation and soils. The aim of this review is to illustrate the effects of global change on the Alpine soil ecosystem, which is an optimal marker to record them. The manuscript enhances our understanding of the global change effect on the Alpine environment: on morphology, on ice, on vegetation and points out how the cycles of soil nutrients equilibrium have been changed with a direct effect on soils that support plant species. The changes in cryosphere, glacier reduction and periglacial environment as glaciers retreat, decrease in the snow cover extent and earlier snowmelt, determine an effect on soils (on the structure, organic matter and humus forms, soil processes and soil types) from the top of the Alpine horizon to the bottom. The processes induced by climate change (such as erosion and tree line shifting) have a direct effect on water balance that can be observed on soil profile characters with an effect on upward migration, change in phenology, extensive losses of species. The equilibrium of the biogeochemical cycles has been changed and this has a direct effect on soils that support plant species.

Keywords: Alpine environment; cryosphere; soil science; treeline

The European Alpine belt is a mountain range stretching along an arc of about 1,200 km (190,000 km^2), with about 13 million inhabitants. It has not only an environmental value but also a social one [e.g. the amount of water delivered by the Alps allocates 40% of EU consumption, see EEA (2009)]. The importance of the Alps has been declared officially on March 6th, 1995, when the Alpine Convention came into force, signed by five OECD members. It has been declared that the Alps are a territory with a large biodiversity and with a delicate balance that needs protection, and then the International Commission for the protection of the Alps (CIPRA) has been established. Recent studies have shown that it is very important to define the evidences of the global change to monitor the Alpine ecosystems, in order to protect and support the Alpine landscapes, habitats and biodiversity and to suggest appropriate forest, farming, environment management and policies of the European society (OECD 2007; Gobiet et al. 2014). It is known that the climate plays an important role in every ecosystem, particularly in the Alps, where meteorological factors, combined with severe morphological conditions, often show extreme behaviours.

The climate is a principal factor governing the natural environment of mountains on short-time scales (Beniston 2001), and it characterizes the location and the intensity of biological, physical and chemical processes (Vranová et al. 2011; Bradley et al. 2015). Mountain climates are governed by four major factors, namely continentality, latitude, altitude and topography. Altitude is certainly the most distinguishing and fundamental characteristic of mountain climates (Chimani et al. 2013;

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Morán-Tejeda et al. 2013), while topographic features play a key role in determining local climates, in particular due to slope, aspect and exposure of the surface to climatic elements (Beniston 2006; Liancourt et al. 2013).

The singularity of the Alpine climate is a high degree of complexity, due to interactions between the mountains and the general circulation of the atmosphere (Samec et al. 2006), which result in features such as gravity wave breaking, blocking highs, and föhn winds. A further cause of complexity results from the competing influences of a number of different climatological regimes, namely Mediterranean, Continental, Atlantic and Polar (Beniston 2005).

The complex topography of mountain regions, especially in young ranges as the Alps, determines sharp gradients in climatic parameters, in particular temperature and precipitation, also over very short distances. As a consequence, mountains exhibit large biodiversity, often with sharp transitions from vegetation and soil to snow and ice (Beniston 2006; Schworer et al. 2014).

Mountains are susceptible to the impacts of a rapidly changing climate and provide interesting locations for early detection and study of the signals of climate change and its impacts on hydrological, ecological and societal systems (Cannone et al. 2008; Kohler, Maselli 2009; Sugiero et al. 2009; Wolf et al. 2012). Human settlement does not explain the marked differences between the potential and contemporary actual vegetation in the Alpine environment (Gerlach et al. 2006; Evershed 2008; Hjulström, Isaksson 2009; Miehe et al. 2014) – the ecological continuity of parent material and the nowadays vegetation was broken by both processes occurring after Dryas 3 (the end of the Würm period) and the continuing Holocene global climate changes (Simonneau et al. 2012). Therefore, the Alps represent unique areas for the detection of global change and its environmental involvements because of several reasons: 1 – as the climate changes rapidly with altitude over relatively short horizontal distances, so do vegetation and hydrology (Scherrer, Körner 2011) and relatively small perturbations in global processes can cascade down to produce large changes (Helbing 2013); 2 – in mountain ecosystems, it is possible to investigate impacts of global warming in the absence of direct or significant human interference (Beniston 2006; You et al. 2014); 3 – because of the abundance of available literature data and monitoring actions about climate and environment in their territory. In addition, the Alps represent unique areas also from the viewpoint that such changes of vegetational cover had a considerable effect on the water balance of biotopes (D'Amico et al. 2014). When the vegetation structure changes, alterations of transpiration flow, accumulation of snow and its melting speed, soil surface evaporation and a depth of soil freezing modify those processes that control the water balance of a habitat (Beniston, Stoffel 2014; Zongxing et al. 2014).

The climate in the Alps from the late 19th century to the end of the 20th century was characterised by an increase of the mean annual temperatures by about 2°C, by a more modest increase of maximum temperatures and by a trend in the average precipitation data (Beniston 2006; Auer et al. 2007; Solomon et al. 2007). It is estimated that the atmospheric CO_2 will rise and it will increase the surface temperature of the Earth by 0.25°C per decade throughout the current century (Gobiet et al. 2014). The aim of this review is to summarize the principal highlights of the climate change consequences in the Alpine environment with a special focus on the soil and to emphasize some of the elements of interactions between the soil, the vegetation and the environmental components.

Background and aims

We analyse recent literature to describe the effect of the global change on the Alpine land: on morphology, on ice, on vegetation and on soil, from the top of the Alpine horizon (2,400–2,600 m above sea level) to the bottom. With regard to the response of soils to climate change (Rejšek 2004) dominant soil processes and their distribution are taken into account using the classification of the IUSS Working Group WRB, 2006. The discussion about the organic horizons of soil was referred to in Zanella et al. (2011).

The effect of climate changes on landscape dynamics can be investigated on geomorphic features deposited or produced during the Late Glacial Maximum or Holocene period (Kramer et al. 2010), when a dramatic temperature increase was recorded within a relatively short time interval (Stoffel et al. 2014). That situation was similar to what is happening nowadays in lands with similar climate and contextual challenges such as North America, Australia (Snowy Mountains) and New Zealand.

The velocity of landscape dynamics can be assessed by studying the tree line shifting and through a combination of relative (Goudiet 2006) and absolute dating techniques applied to soil and charred material, or/and to rocks (e.g. Favilli et al. 2008, 2009; Hormes et al. 2008; Cossarta 2010).

Regional Circulation Models applied to the European Alps, General Circulation Models and the Intergovernmental Panel on Climate Change Fourth Assessment Report represent an effort to characterize the Alpine climate in the latter part of the 21st century (Solomon et al. 2007).

We have considered all the cryosphere components: glaciers, permafrost and snow. Regarding the periglacial environment, we investigate the variation of snow cover, the retreat of glaciers. We analysed the morphological aspects related to slope stability and hydrology like in the case of "rock glaciers", and also the signs within the soil (e.g. stability of aggregates) that are the "memory of the soil" (Targulian, Goryachkin 2011) and indices of soil erodibility. The authors state that different acclimation mechanisms of various floral taxa led by their distinct water demands and responsiveness to draught have been reflected in some soil parameters such as soil structure, soil organic matter (SOM) and its mineralization that interact with the nutrient cycle and microbial communities and are strictly dependent on climate change (Bradley et al. 2015).

The cryosphere and glacier recession

In the climate system, the cryosphere (which consists of glaciers, permafrost and snow on the land and lake and sea ice as well) is intricately linked to the surface energy budget, water cycle, sea level change and surface gas exchange (Wojciech 2012). The cryosphere integrates climate variations over a wide range of time scales; it is a natural sensor of climate variability and provides a visible expression of climate change. In the past, the cryosphere underwent large variations on many time scales associated with ice ages and with shorter-term variations like the Younger Dryas or the Little Ice Age (Solomon et al. 2007; Chiri et al. 2015).

Solomon et al. (2007) shows that at the present time, snow covers more than 33% of lands north of the equator from November to April, reaching 49% coverage in January. Since the early 1920s, and especially since the late 1970s, the snow covered area (SCA) in the Northern Hemisphere has declined in spring and summer, but not substantially in winter. Over the 1922 to 2005 period, the linear trend of the SCA in March and April has undergone a statistically significant reduction of 7.5 ± 3.5% (Solomon et al. 2007). Beniston (1997) showed that since the mid-1980s, the length of the snow season and snow amount have substantially decreased in the Alps, in particular at altitudes below 1,500 m and found a possible reason for this in the presence of persistent high surface pressure fields over the Alpine region during autumn and winter, which are characterized by warm temperatures and low precipitation (Bocchiola, Diolaiuti 2010; Soncini, Bocchiola 2011). The Alpine temperature and precipitation variability and the fluctuations of high pressure episodes are strongly correlated with anomalies of the North Atlantic Oscillation index and they are controlled by the atmospheric circulation modes (Casty et al. 2005). Other studies confirmed that the days with snow cover on the ground decreased in the last twenty years, particularly in sites at mid and low altitudes, where the duration of continuous snow cover and the number of snowfall days decreased and precipitation changed from solid to liquid state, with subsequent more rain on snow events in spring time (Laternser, Schneebeli 2003; Szczypta et al. 2015). The role of snow in the climate system includes strong positive feedbacks related to albedo and other weaker feedbacks related to moisture storage, latent heat and insulation of the underlying surface (Déry, Brown 2007; Qingbai et al. 2015). The lack of snow cover reduces the degree of insulation and results in cold soil temperatures, extensive soil freezing and increase in freeze/thaw cycles, influencing soil microbiological activity and SOM (Soil Organic Matter) mineralization (Edwards, Cresser 1992; Groffman et al. 2001; Clement et al. 2012; Welc et al. 2014). Glaciers are among the most important elements of the cryosphere and many works have been written in the last years which studied glacier variations in relation to global warming (Le Roy et al. 2015). The first field survey to detect glacier terminus fluctuations started in Switzerland at the end of the 19th century and later in Italy and France (in the Alps). In some cases, data dating back to the 17th century are available but not from direct field surveys. These long series were reconstructed from dendrochronologic evidences or are based on other glacier proxies. A method to evaluate the retreat or advance of glaciers was to measure the length variation of glacier tongues (Oerlemans 2005), while recently (mid-20th century) glacier mass balance measurements have been performed to assess the gain or loss of ice volume, with particular attention to hydrological purposes [WGMS (ICSI-IAHS), several years].

In general, during the last decades, after the short positive impulse at the end of the 1980's, Alpine glaciers have been continuously retreating. The Italian Alpine glaciers have decreased their area up to 20–22% in the time window 1990–2003 in Lombardy (Citterio et al. 2007; Diolaiuti et al. 2012), up to 30%

in the time frame 1975–2005 in Aosta Valley (Diolaiuti et al. 2012) and a decrease by about 40% of their area was found studying Ortles Cevedale glaciers in the period 1954–2007 (D'Agata et al. 2013). From 1850 to 2000, glaciers in the European Alps lost almost 50% of their area, the largest reduction (22%) occurred after 1985 (Zemp et al. 2006). For nine measured glaciers in the Alps, Zemp et al. (2005) estimated a mean loss of about 600 $kg \cdot m^{-2} \cdot yr^{-1}$ from 1980 to 2001, with an exceptional mass loss of 2,500 $kg \cdot m^{-2} \cdot yr^{-1}$ during 2003. In terms of the volume, Alpine glaciers have lost on average 1% of their volume per year since 1975, being reduced from 105×10 km^3 to 75×10 km^3 at the beginning of the third millennium (Paul et al. 2004). Zemp et al. (2005) supposed that the Alpine glacier cover would decrease by 80% until the middle/end of this millennium if there were an increase in temperature by 3°C, as expected if humans did not start to react to climate change by adopting mitigation policy (Solomon et al. 2007). An important aspect is that the air temperature has a higher effect on the glacier mass balance than precipitation; therefore an increase in precipitation by 20% will bring only the previous value from 80 to 65% (Zemp et al. 2005). From the vegetation point of view, such a decrease in the Alpine glacier volumes (Solomina et al. 2015) led to the ongoing process of re-colonisation and development of new ecosystems (Pichler et al. 2007) in which the fast decline of pioneer vegetation occurred. Besides, at the elevation threshold of 2600 m a.s.l. the resident species may create a migration barrier for the new colonization (Cannone et al. 2008; Cannone, Pignatti 2014).

The higher temperature causes the contraction of snowbeds that shift to higher altitudes where the snow-dependent plants that decrease in coverage may find the refuge (Cannone et al. 2008).

The periglacial environment

The deglaciated areas, where soils and rocks are exposed to different conditions, are called periglacial environment. The term periglacial was first introduced to describe the climatic and geomorphic conditions peripheral to the late Pleistocene ice sheets but the term has undergone a substantial revision and no universally accepted definition exists. The term has been generalized to include those environments where climatic conditions result in severe frost action that dominates geomorphic processes (French 1976).

In the periglacial environment, permafrost has been developed – ice is formed within both the soil and the cracks in rocks. The term permafrost "vechnaja merzlota" (eternal frost) was first introduced to describe the condition of earth materials that remain below 0°C continuously for two years at least (Muller 1945; Muller et al. 2008). It was observed for the first time in the everlasting thick frozen grounds of Central Siberia. It is defined exclusively on the basis of temperature, irrespective of the type of earth material, water content, degree of indurations, or lithological characteristics. The distribution and thickness of permafrost is governed by the energy balance between the earth and the atmosphere (Gerrard 1992; Gu et al. 2015). The permafrost is associated with the high C-stocks (down to the C horizon or rock surface it is 10 to 15 kg/m^2 by Zollinger et al. (2013).

Permafrost in the Alps is negatively affected by the global change, mainly due to warmer air temperature, lower snowfall and shorter winter season. According to Solomon et al. (2007) and Li et al. (2015), the decrease of the thickness and/or the extent of permafrost is a worldwide ongoing process that is increasing the permafrost active layer (Schuur et al. 2008; Wang et al. 2014).

Rock glaciers are typical geomorphological features of the periglacial environment and are characteristic of high mountain permafrost. They are made up of debris and ice that creep on slopes at a typical rate of a few decimetres per year (Serrano et al. 2006). They are indicators of the present-day climate (especially thermal conditions) and have also been used for reconstructing the palaeoclimate and landscape evolution. Detailed rock glacier dynamics was investigated in arctic and Alpine environments in the late 20th century (Serrano et al. 2006; Haeberli et al. 2007). The obtained displacement rate in the frontal part of the alpine rock glacier is up to 0.6–0.9 $m \cdot yr^{-1}$ (by geodetic data, Lugon, Stoffel 2010). The relict form and the dynamics of rock glaciers are usually related to palaeoclimatic changes (e.g. Frauenfelder et al. 2005; Kääb et al. 2007). For instance, speed variations change with frequencies in the order of several decades or centuries and can result from a general spatial-temporal modification in boundary conditions, such as material and water/ice supply or thermal regime, or terrain topography (Frauenfelder et al. 2005). Photogrammetric and geodetic monitoring series of several decades suggest that velocity changes of the mountain permafrost creep at pluriannual time-scales may be due to variations in weather and/or climate conditions (Paul et al. 2004; Roer et al. 2005). At shorter time-scales, the sensitivity of the creep of frozen slopes to external climate forcing is strongly dependent on individual internal conditions of rock glaciers, as clearly shown by observations of seasonal velocity variations (Kääb et al. 2007).

The question how the weather and the atmospheric warming, which are currently observed in many mountain regions (Kääb et al. 2007), may influence the creep of perennially frozen debris has not been completely solved. Kääb et al. (2007) showed the potential reaction of perennially frozen slopes to ground temperature variations. Boeckli et al. (2012) developed a statistical approach to modelling permafrost distribution in the Alps and they developed a theoretical model of mountain permafrost reaction to climate change. Davies et al. (2001) found the minimum shear strength of frozen rock joints at temperatures between –1 and 0°C using centrifuge modelling. Furthermore, some authors have collected various indications that the deformation of frozen debris or rock glaciers increases with increasing ground temperatures (e.g. Gruber, Haeberli 2007), or have proposed creep laws which include a dependence on the ground temperature (Kääb et al. 2007).

As above-mentioned, changes in phytocoenoses affect the soil evolution. The distinctive points related to studies of changes affecting the alpine environments (Cannone, Pignatti 2014; Egli et al. 2014) can be seen especially in uncertainties in the roles of soil biomass, carbon (Bradshaw et al. 2015) and nitrogen (Qi et al. 2011) controlled by local climate oscillations (Xu et al. 2015), interrelationships between the microrefuges and the local geomorphology (D'Amico et al. 2014; Gentili et al. 2015) and synergic effects that reinforce these processes (Smith-McKenna et al. 2014). The usefulness of local studies focused on distinctive reasons (Anderson et al. 2011; Bowman et al. 2012) is also indisputable. Díaz-Varela et al. (2010) described a novel procedure to delineate the current and former state of ecotones of alpine phytocoenoses which was tested in the Italian Alps for the period 1957–2003 showing a trend of an increase in altitude for the ecotones scrutinized. The permafrost degradation is associated with the vegetation cover decline and dynamics (Cannone et al. 2008). Ecological responses of plant species and communities to climate change show a range filling processes with downward shifts of the persisting species (Cannone, Pignatti 2014). Rydgren et al. (2011) and Valese et al. (2014) highlighted the role of human disturbances in the alpine environments for a direction in vegetation succession and reinforced the role of soil properties (Burga et al. 2010), soil texture in particular.

Geotechnical changes of frozen slopes and short-term changes in triggering rainfall have a notable impact on slope stability, and are thus of interest for dealing with applied problems such as construction stability, debris-flow hazards, or rockfall hazards (Noetzli et al. 2007; Kääb et al. 2007; Bollschweiler, Stoffel 2010).

Moreover, increasing the thickness of the permafrost active layer and changes in hydrology at higher altitudinal levels will change the ecological conditions on steep mountain slopes, making them much more unstable, especially where the incidence of precipitation events grows, probably causing a higher frequency and maybe intensity of avalanches and landslides (Beniston 2006) and higher erosion rates (Fischer et al. 2013).

Specificity of soils in Alpine ecosystems

Soil structure

To study the effects of global change on soil structure and physical properties, obviating the complex mechanisms that bound climate and structure genesis, it is required to investigate aggregate stability. This soil property is a good indicator of soil structure susceptibility to runoff and erosion (Nyberg et al. 2001; Barthès, Roose 2002) and, according to Lavee et al. (1996), of the soil degradation status as a consequence of global change, because it is sensitive to warming and because it responds seasonally to precipitation (Brunetti et al. 2006).

Barthès and Roose (2002) demonstrated that the topsoil aggregate stability is closely and negatively related to soil susceptibility to erosion by runoff, especially in consideration of slope gradient and climate aggressiveness. Aggregate stability is expected to decrease with an increase in the frequency of dry periods followed by almost instantaneous flash flood phenomena, as a consequence of an embittered slaking effect. This phenomenon, especially in soils with low exchangeable sodium percentage and swelling clay content, like most Alpine poorly developed soils, may be considered the most important mechanism contributing to the soil aggregate breakdown. This process is recorded in the clay cutans of horizons with the "soil memory" (Targulian, Goryachkin 2011) of the climate change related with a moisture regime change. The more humid climate is linked with more illuvial cutans that are records of humid percolating conditions and translocation of clay. Silt and clay particles within the soil body (cutans as structuring agents in Bt horizons) are records of increased aggressiveness of the solution along fissures, which destroy silicates in cutans more intensively (Targulian, Goryachkin 2011).

Aggregate stability has already been used as soil erodibility indicator in the Universal Soil Loss Equation (Wischmeier, Smith 1978) to model erosion rate by measured losses of soil.

However, the amount of field data available for establishing the influence of climate change impacts on the multivariate factor of aggregation and on several key processes of water erosion is very limited, also considering the multiple effects that climate expresses on ecosystems (Confortola et al. 2013). Moreover, despite their importance in Alpine Regions, according to Solomon et al. (2007) it appears that the analysis of extraordinary rainfall events and their effects on ecosystems is still underdeveloped, like the impacts of global change on soil structure and alpine soil susceptibility to erosion (Kirkpatrick et al. 2014).

Cryosols, Regosols, Fluvisols and Leptosols

Strongly related to a decrease in the extent and an increase in the altitude of permafrost are Cryosols, i.e. the soils which show evidence of cryogenic processes (Arkhangelskaya 2014), cryoturbation and contain water in solid form (permafrost condition). The horizons are cryoturbated, they show frost heave, thermal cracking, ice segregation and patterned ground microrelief. They occur on top of the Alpine horizon (2,400–2,600 m a.s.l.) and are very vulnerable to the change of temperature. They are associated with the specific belt where the soil temperature is continuously below 0°C for several years at least (Kurylyk et al. 2014). Obviously, the global climate changes have an impact on permafrost geothermal regimes in the Alpine mountains (Harris et al. 2010). The raising of the suitable lower boundary (Bauman et al. 2014) for Cryosols (and their consequent reduction), which is correlated with the increase of the permafrost lower boundary, has great consequences in the Alpine environment (Fouché et al. 2014) where the slopes are not stabilized, rockfalls or landslides might occur at high elevations, causing serious impacts on the valleys behind. Many projects are monitoring permafrost (for example, the European projects such as PermaNET – Long-term Permafrost Monitoring Network, and PERMOS project – Swiss Permafrost Monitoring Network). If we correlate the global warming with increasing meteoric events, we can suppose that the area occupied by Cryosols will decrease while that of soils like Fluvisols increases. With the melting of permafrost, the water will be most available and it will flow in areas of alluvial cones and Fluvisols will increase their range. Fluvisols are genetically young soils, azonal soils on the more stable portion of alluvial cones, on the high Old Holocene terraces and lacustrine deposits (Simonneau et al. 2012). Their profiles show evidences of stratification, different granulometry is an indicator of the energy and duration of the past climate events. The organic horizon of Fluvisols is primarily a humus form of Mull with humified and biologically very active organic matter. The Mull starts to be formed when the vernal snow cover leaves the soil free.

In mountain areas higher temperatures ensure a longer duration of the vegetation season, a reduction of the frequency of frosts and therefore the better coverage of the ground surface, the development of humus forms of Mull reducing erosion rates and increasing the stability of soil.

Vice versa, in some upland areas, erosion rates will be reduced as a result of the better soil surface cover and topsoil stability arising from higher temperatures that extend the duration of the growing season and reduce the number of frosts. Cannone et al. (2007) described two patterns for the pioneer vegetation: (*i*) at lower altitudes, the area of pioneer vegetation increases especially in the vicinity of streams, alluvial and debris flow fans, and (*ii*) at higher altitudes, there is a regression in the areas of pioneer vegetation, on steep slopes in particular.

Today Regosols occupy a very large area. Regosols are young, undeveloped soils, composed of a wide variety of textures displaying the Moder humus form which relates to the prominent fungi and arthropod activities (Chersich 2007). Under a warmer climate the Regosol area will be reduced because it is very likely that developing Bw horizons will start massively.

The biological activity will tend to increase and with the incorporation of organic matter a developed structure is expected to form (with transformation of humus from Moder forms and Mull and the formation of granular structure and subangular polyhedrals; Chersich et al. 2006). Bulk density and pH will increase while organic acids and the cation exchange capacity decrease.

Histosols and Gleysols

Organic matter stored in the soil represents one of the greatest reservoirs of organic carbon at a global scale and the mineralization of its part could represent an input of CO_2 in the atmosphere with consequences on climate change (Von Lützow et al. 2006; Fontaine et al. 2007).

With regard to the great importance SOM has for the global balance of CO_2 (Lal 2004; Schmidt et al. 2011) the study of its potential biodegradability in a warmer environment is currently one of the topics of greater interest in the scientific research (Davidson, Janssens 2006; Uhlířová et al. 2007). The soils more related with SOM are Histosols and Gleysols that can occur in the peat. Histosols are soils with a thick organic layer, with redoximorphic features in particular in that part of the profile that has been in contact with water. Gleysols occur in all wet sites also near rivers or brooks and ponds. They have an under groundwater influence where there are evidences of reduction processes. The layers have generally darker colour with greyish/bluish (redox), reddish, brownish or yellowish mottles on the ped surfaces. They have a wide range of parent material: unconsolidated materials, fluvial, lacustrine sediments of the Pleistocene or Holocene age.

The severe acidity of some Gleysols and Histosols (with the humus forms of Hydromoder or Tangel) allows the soil memory function. The soil memory function is also shown by the Hydromull humus form that is more common on peat (that started their formation during the Atlantic period: 8000–5000 years ago). They are suitable to conserve pollen, spores, phytoliths, remnants of plants such as old wood that can testify the presence of different environment than the present one, so they can give evidence of global change in the past (Stepanova et al. 2015). The peat soils have a large accumulation of organic matter. The European Community is very sensitive to the conservation of this habitat because with its deterioration (and peat mineralization) great amounts of CO_2 could be released. The wetland vegetation experienced a regression, especially at lower altitudes (Cannone et al. 2008).

Soil organic matter (SOM) and nutrient dynamics

The protection of SOM from degradation is mainly due to three mechanisms: (1) physical stabilization of organic matter in soil and to its inaccessibility due to establishing physical barriers between microbes and enzymes and their substrates (Six et al. 2004; Von Lützow et al. 2006); (2) chemical stabilization, which consists in intermolecular interactions between organic substances and minerals with complexation of functional groups of organic molecules with metal ions that decrease the availability of the organic substrate (Guggenberger, Kaiser 2003; Mikutta et al. 2006); (3) biochemical stabilization, caused by molecular structures inherently stable against biochemical decay such as condensed and lignin-derived aromatic carbons, melanoidins, some tannins or aliphatic compounds, humic polymers and charred materials (Krull et al. 2003; Von Lützow et al. 2006). However, the relative contribution of each mechanism to the organic matter preservation in soil is unknown (Baldock, Skjemstad 2000; Six et al. 2002; Mikutta et al. 2006; Von Lützow et al. 2006).

In Alpine ecosystems SOM may be protected not only by the above cited mechanisms, but also by the low soil temperature. The processes of SOM stabilization are temperature dependent since biotic and abiotic reactions of degradation and condensation that produce new aromatic structures with larger molecular weights are slowed down by cold temperatures. Moreover, the formation of organomineral associations is also slowed down, as the partial oxidation of organic molecules necessary to promote adsorption to the mineral surface and/or binding with metal ions (Grünewald et al. 2006) is also temperature dependent.

A major component of SOM of cold environments is labile C with a high potential of biodegradability in a warmer environment (Dai et al. 2002; Mikan et al. 2002; Weintraub, Schimel 2003; Shaver et al. 2006). Moreover, the soils of cold environments are characterized by a dense microbial community with a high growth potential (Anesio et al. 2009) that is comparable, like total biomass, with that of temperate soil ecosystems. Therefore, organic matter of alpine soils may be highly susceptible to the actual global warming (Schimel et al. 2006), which causes permafrost melting (Christensen et al. 2004; Gruber, Haeberli 2007), increase in soil temperatures (Chudinova et al. 2006) and extension in the length of the growing season (Euskirchen et al. 2006).

Another SOM protection mechanism occurring in the Alpine ecosystem, both in permafrost-affected soils and in soils frozen for many months per year, is the freezing effect (Davidson, Janssens 2006; Uhlířová et al. 2007). In this kind of soils, even if the enzymatic reactions can occur below 0°C (Mikan et al. 2002), the diffusion of substrates and extracellular enzymes within the soil is extremely slow when the soil water is frozen. SOM of the cold environment, buried in the deep soil layers through cryoturbation, has more low-density physical fractions that are potentially easily degradable (Zollinger et al. 2013). In these environments SOM has been preserved until today thanks to the prevailing cold conditions that have constrained its decomposition (Mikan et al. 2002). However, following the warmer conditions the global change is expected to produce, the easily degradable organic matter will lead to a transformation of the long-term cryopreserved SOM with the release of large amounts of CO_2 and nutrients, and the production of more humified SOM that will enhance the vegetation growth (Zollinger et al. 2013).

In Alpine soils there is a close link between microbial SOM transformations and nutrient availability as for P and N elements (Weintraub, Schimel 2005) when in this environment these transformations are an important limiting factor for primary production (Kaiser et al. 2005). Therefore, the intensive SOM mineralization produced by the global change in the Alpine environments could bring a higher availability of N and P, which will increase the assimilation of nutrients by plants but not by microbes (Schmidt et al. 2002).

The greatest part of the knowledge dealing with the effects of global change on SOM and nutrient dynamics is due to laboratory incubation researches (Freppaz et al. 2014). The great importance of snow precipitation on nutrient dynamics and also the effects of snow thickness on microbial community and SOM dynamics are well known facts (Hiltbrunner et al. 2005; Tan et al. 2014). For these reasons, it should be necessary to consider all the factors which could influence the climate of Alpine environments.

Erosion processes

Bouwer (2011) stated that the global soil losses by erosion and landslides have escalated enormously over the past few decades. Consequently, the Alpine soil erosion under the global climate changes becomes one of the most important topics of European research.

According to Christensen and Christensen (2003) and others (i.e. Beniston 2003), reductions in average summer precipitation and consequent episodes of summer drought may be simultaneously accompanied by a sharp increase in short but potentially-devastating heavy precipitation events (Casty et al. 2005; Beniston et al. 2011), such as flash floods, more frequent overflow of storm drainage facilities, greater soil erosion and higher risk of landslides in unstable areas (Bollschweiler, Stoffel 2010). Where the climate change is expressed by extreme events, the erosion will be stronger, and the extent of Leptosols might be larger. Leptosols are azonal soils, weakly developed directly on the rock (within 25 cm from the soil surface), or where the erosion has removed the upper part of the soil profile. Leptosols are shallow, often extremely gravelly soils, so they have severe limitation to rooting. The forms of humus more frequent also in this case will be those of Mull: Mesomull, Dysmull (Chersich 2007).

The assessment of the impacts related to global change on the soil structure and its resistance to erosion is not easy to determine, because of the complexity of interrelated factors to consider (Park et al. 2014). The relationship has two faces. On the one hand, climate exercises an indirect influence on the soil structure affecting factors correlated with aggregation such as SOM (Von Lützow, Kögel-Knabner 2009), soluble salts and amorphous iron oxides (Mikutta et al. 2006), wetting-drying and freeze-thaw cycles which in turn affect land use (Ping et al. 2008), vegetation covers and biological cycles (Six et al. 2004). The structural improvement of soil, due to the ped aggregation, will lead to a predominance of humus forms in Mull (Chersich et al. 2006). Their effects on the soil structure can be positive or negative and structural characteristics are the dynamic result of their complex interaction. On the other hand, climate change affects the soil structure directly through the increase of extreme precipitation events and snow-melt, which could raise the frequency and severity of floods (e.g. the flood risks are more frequent than in the past; Allamano et al. 2009) and runoff. The types of soils will see a decrease in the area of Cryosols (and probably of Regosols) in favour of an increase in Leptosols and Fluvisols.

The lower Alpine horizon: tree line shifting and podzolization shifting

The upper altitudinal limit of trees is known as the tree line, although it is not usually a distinct line but a steep gradient of increasing stand fragmentation and stuntedness (Körner, Paulsen 2004). The tree line has been directly affected by the exploitation of mountain forests which was partly followed either by practices that favoured certain species (Pitkänen et al. 2003) or by spontaneous secondary successions (Bradshaw 2004). This important boundary (Forrest et al. 2012) is observed in all parts of the world, and it exhibits common features (Holtmeier, Broll 2005). Currently there is much interest in the rate at which the tree line may advance in response to environmental change, especially global warming (Smith et al. 2009). The reason for renewed interest in the tree line is clear: an advancing tree line, or a denser forest below the tree line, would have significant implications for the global carbon cycle (increasing the terrestrial carbon sink) and for the biodiversity of the Alpine ecotone as ousting rare species and disrupting plant communities (Walther et al. 2005; Berthel et al. 2012;

Prietzel, Christophel, 2014; Vilmundardóttir et al. 2015). Presently it is really difficult to study such a role of forests in detail; Parviainen et al. (2000) stated that natural forests represent only 1.7 % of the total European forest area. Nevertheless, the transfer of knowledge from virgin forests (Brang 2005) allows the frame characterisation of ecological conditions caused by an advancing tree line. Therefore, new data on tree-growth dynamics and species adaptation near the treeline (Wieser et al. 2014) under global climate changes (Piermattei et al. 2014) can be combined with changes in the dynamics of forest soil processes.

There are at least three aspects of environmental change to which plants are generally thought to response: increasing temperature, rising concentration of carbon dioxide and increasing deposition of nitrogen (Stanhill, Cohen 2001). Several studies carried out in the Alpine environment (e.g. David 1993 in the French Alps) have demonstrated that during the Boreal period (5000–9000 years BP) the tree line was placed higher than it is at present. Plants may well respond to warming as this will increase the rate of cell division and therefore the rate at which the assimilated carbon can be utilized (Zhu et al. 2015). Warming will also prolong the growing season and, in the already short growing season at the tree line, this effect will be proportionately greater than in lowland or more southern conditions. In the European Alps, during the last century, the total annual mean temperatures increased by about 2°C (Auer et al. 2007), which is above the observed global increase in temperature by 0.74°C over the last century (Solomon et al. 2007). Since Alpine trees are climatically determined ecotones and they are particularly sensible to altered temperature regimes (Theurillat, Guisan 2001), the predicted climate warming is expected to structurally change the tree composition and to raise the tree line. In the Swiss Alps, more recent results have confirmed these findings and reported a strong warming since the 1980s (Rebetez, Reinhard 2008). Walther et al. (2005) found that the vegetation change in the south-eastern Swiss Alps has accelerated since 1985, which was consistent with the increased temperature regime observed at the same sites. Data collected from the South Ural region (Kapralov et al. 2006) showed that in the last 50 years the upper boundary of low forest has ascended, with considerable changes in the composition, density and height of the tree layer. The response of forest trees to increasing atmospheric carbon dioxide is still an open question. The experiment carried out by Körner et al. (2005) was based on the efflux of pure CO_2 into tree canopies through a fine web of woven tubes (web-FACE, Free Air CO_2 Enrichment) at a concentration of 530 ppm over 4 years. The data suggested no lasting growth stimulations by CO_2 enrichment in mature trees after 4 years, while young trees showed continuous growth stimulation. The uptake of carbon was not reduced and no more carbon was trapped but it seemed that the plants pump more carbon through their bodies (Hoffmann et al. 2014). Another possible limiting factor could be the supply of nitrogen (Guidi et al. 2014). From the global warming point of view, a rising tree line will be reflected in increasing biomass (from 15 to 75 t C·ha^{-1}), which would produce a warmer microclimate and better decomposability of produced litter, increasing root growth and root respiration (Pregitzer et al. 2000) and, at the end of the process, raising the turnover of carbon compensated by a greater carbon input (Ni et al. 2015). The global carbon cycle would remain unaffected and the soil organic matter turnover would increase (Kitz et al. 2015).

The timber line is also the boundary for the podzolization domain because this process requires the presence of coniferous vegetation. The high precipitation rate in Alpine areas results in a lot of water entering in the soil. Related to the timber line, its natural shifting (supported by an anthropogenic pressure) plays a great role in the water balance of the site. The downward moving of water through the soil profile can dissolve large nutrient cations such as potassium and calcium and stimulate the migration of organic matter with Al, Fe complexes. The cation exchange capacity is dominated by hydrogen ions H^+ and Al^{3+}. The more frequent soils under coniferous forests are Podzols developed on aeolian siliceous material including loess, and the humus is mainly an acid one, like Mor or Moder forms (Chersich 2007). The altitudinal rising of podzolization is an evidence of the global change recorded in the soil. The past of the climatic change has already been recorded. In the Alps it is common to find Podzols over the timber line. The spodic horizon, which could be considered the "soil memory" (Targulian, Goryachkin 2011), points out a warmer climate than the present one which allowed the podzolization (going back to 130000–75000 years ago when there was the last interglacial period). In the same way, if the climate is warmer than now, we will find the timberline and podzolization at a higher altitude and the humus form will be more acid (Pengerud et al. 2014): from the Mull or Moder of the Alpine grass we will observe the Mor form under coniferous forest.

On the south-facing slopes of the Alps we can find Dystric Cambisols or Podzols over 1,600 m a.s.l. under coniferous trees. We find Cambisols in regions that were under the influence of glaciations during the Pleistocene. In the brunification, i.e. in the main processes for Cambisol formation, it is evident the polyhedral subangular soil structure and Bw horizons have mostly brownish coloration with an increase of clay percentage and/or carbonate removal. Changes in the vegetation cover and the extent of cryosphere can be recorded into the soil profile. Therefore in the Alpine environment we can distinguish soil processes linked with the altitudinal belt (e.g. podzolization, brunification, cryoturbation) and others referred to the particular zone (gleyfication and stratification near a water source).

Below the tree line, due to the effect of temperature intolerance, the alpine species cannot withstand the intensity of the competition. Above the tree line, an upward migration of the species on mountain summits has been observed with upward shrub displacement and an increase of species richness, which may be a transient effect of the habitat fragmentation or a long-term effect of the vegetation succession (Cannone, Pignatti 2014).

Impact of soil processes induced by climatic changes on socio-economic sphere

In the Alpine region, an increase in the frequency of intense rainfalls (> 30 mm/day) and permafrost degradation linked to the climatic changes (Einhorn et al. 2015) could determine a change in the water regime of soils, promoting an increase of the soil moisture and causing the persistence of saturated or close to saturation conditions all the year round. These conditions are responsible for triggering erosion processes, debris flows and landslides (Collison et al. 2000; Lu, Gsodt 2013) and they can represent preparatory factors for flood triggering (jomelli et al. 2009). Climatic modifications also cause a change in land cover due to different rainfall and temperature conditions. In particular, the shifting of the tree line to a higher altitude can cause the development of bare soils or grasslands and shrub lands, which are more susceptible to soil erosion, shallow landslides and debris flows which develop in mountain regions (Begueria 2006).

The increases in landslides and flood susceptibility related to climate change have negative effects on the landscapes and on the people (Crozier et al. 2010). Landslides and floods affect the surface soils developed on hillslopes, provoking the loss of highly productive soils (loss of organic matter in soils, degradation of the ecological functions of soils) and the partial or complete destruction of crops planted in steep terrains. An example of the consequences of landslide development for crops in steep terrains of the Alpine region is the destruction of terraced slopes with vineyards and the subsequent economic losses for the intense rainfall event of 14–17 November 2000 in the Valtellina area (Central Alps, Italy) (Crosta et al. 2003).

Moreover, the increase in landslides and flood susceptibility could be responsible for higher risks for the human structures, like blockage and destruction of roads and railways with subsequent isolation of towns and buildings and, as a consequence, for the people living in hazardous areas (Einhorn et al. 2015). Thus, better assessment of the soil and environmental conditions will become fundamental that lead to triggering landslides and floods in relation to the forecasted climate change effects, for reducing the hazard and the risk linked to these types of phenomena.

Comparison of approaches and conclusions

During the 21st century, the most recent climate modelling, based on a range of scenarios, shows an increase in annual temperature by 0.1–0.4°C per decade (Alcamo et al. 2007) when a rise in precipitation in the north, its decrease in the south, an increase in the seasonality of precipitation and prolonged dry periods are expected. Thus the global warming would bring warmer and more humid conditions in winter and much warmer and drier conditions in summer. This would be connected with an increase in the frequency of intense precipitation events like rainfalls. Many uncertainties arising from the ongoing environmental and socio-economic processes (Kauppi 1996) have likely been expected.

The aim of this study was to review the papers concerning the effects of global change on the Alpine ecosystem, which is very sensitive to climatic changes, therefore an optimal marker to record them. In particular, we observed the global change in pedosphere in relation with cryosphere and biosphere. In particular, effects on the flora through distributional changes of species across climate scenarios (Thuiller 2004) seem to be very presumable.

As for cryosphere, the immediate consequences are the loss of about half of the European Alpine glacier mass during the past 150 years and a decrease in the snow cover extent. In recent model studies, the snow at low to medium elevations will disappear by 2100

(Beniston 2012), a more pronounced decrease in snowfall volumes of the Italian Alps is projected around 2060 (Soncini, Bocchiola 2011). These evidences are related with the pedosphere. The particular knowledge of interrelationships between the soil type formation and the dominating phytocoenological society related to climate development was described by Pichler et al. (2011). Concerning the physical conditions of soil, the increasing thickness of the active layer can determine the destabilisation of slopes and, together with an increase of intensive rainfall events, cause severe water erosion phenomena, or even debris flows and landslide episodes. It will produce a change in soil structural features, which is also in equilibrium with several factors influenced by climate change. One of the most important factors is SOM. With the increasing soil temperature, the soil organic matter may not be protected anymore (e.g. permafrost melting), with the subsequent release of large amounts of CO_2 and nutrients, producing therefore more humified SOM. The intense SOM mineralization produced by the global change might bring a higher availability of N and P, which, in turn, will lead to greater primary production with the subsequent CO_2 immobilization in the vegetal structure. However, this fact does not seem to be able to balance CO_2 emitted from SOM mineralization (Davidson, Janssens 2006).

In biosphere the global warming will cause an upward migration of alpine plants (Parmesan 2006; Grabherr et al. 2010). In response to the environmental change, the tree line may advance upwards. The podzolization line, which is related to acidification by the coniferous tree litter, may also advance to a higher altitude. The warming will prolong the growing season with subsequent changes in the phenology – e.g. influence on the start of the vegetation period for plant species. An increase in the rate of the cell division and therefore in the rate at which the assimilated carbon can be utilized are expectable. The snowbeds and grassland species will be reduced, especially concerning endemic ones, due to pioneer and early successional species while the transect effect of an increase in species richness has been observed that may confirm the forecast of species loss and habitat fragmentation or a longer effect (Cannone, Pignatti 2014). In this scenario the biodiversity is endangered – based on the relationship between the productivity and diversity of phytocoenoses (Pretzsch 2005).

Regarding the species distribution, it has been observed that the species mainly exhibited downward shifts and the species of the neighbouring communities filled the range of the same altitudinal belt (Cannone, Pignatti 2014). Concerning the related soil variability (Rajkai 2008), the Cryosol (and Regosol) area will be reduced and these soils will be shifted to higher altitudes like the Podzol area, while the Fluvisol and Leptosol area might become larger. It is also fundamental to underline how it is difficult to predict a future scenario because all the different environmental components have a peculiar response to climate change with a specific reaction time (Soncini, Bocchiola 2011). We recognize the important role of the time as a factor of pedogenesis, "times of changes" but at the moment there are no sufficient bibliographic data to give a reaction time for each environmental variable and we can only formulate a hypothesis.

As regards the effects on the socio-economic sphere, a change in the rainfall pattern of the Alpine region could provoke an increase in the frequency of extreme rainfall events, which could allow for triggering a higher number of erosion processes, landslides and floods. These phenomena could have negative impacts on different aspects of the socio-economic sphere of the people living in Alpine regions: (*i*) partial or complete destruction of the crops planted in steep terrains with the subsequent loss of highly productive soils and severe economic damage; (*ii*) significant damage to human structures and buildings; (*iii*) increase in the number of people living in highly vulnerable areas.

As highlighted by this review, it is fundamental to recognize the implications of climate change for the Alps, because it will have consequences not only for the environment but also for the socio-economic sphere. Therefore, the identification of global change evidences is the starting point to raise human awareness and to find an appropriate mitigation strategy.

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