

# THE EFFECTS OF CLIMATE CHANGE ON DECOMPOSITION PROCESSES IN ANDEAN PARAMO ECOSYSTEM–SYNTHESIS, A SYSTEMATIC REVIEW

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**Abstract.** The paramo is a high mountain ecosystem with cold and humid climate, it has high amount of sunlight and cloudiness, furthermore, organic matter has low decomposition rates, hence, leaf litter degradation gets 40% per year as maximum. In the last 70 years, the air temperature near the surface of the Tropical Andes has increased significantly up to 0.34 °C/decade. In the same region, it is estimated that in this century the average temperature will vary from <+ 1.60 °C to >+ 2.61 °C, which exceeds the threshold of natural climatic variability. On the other hand, although precipitation along the Andes has not shown an increase or diminish pattern between 1955 and 1994, it is projected that by the year 2100, it will decrease in the outer tropics and will increase in the interior tropics. In this paper, we discuss how the decomposition of organic matter in paramo areas is influenced by climate change and analyze how current trends of variation in temperature are projected to affect ecosystem processes. Previous studies have determined that the increase of the atmospheric temperature (as long as the humidity remains stable or increases), generates higher decomposition rates, so that an increase of 1 °C in the atmospheric temperature would also mean an increase in the rate of decomposition of up to 10%. These changes would cause the release of the carbon accumulated in the soil to the atmosphere as CO<sub>2</sub>, which would be a determining factor for climate change.

**Keywords:** CO<sub>2</sub>, global warming, greenhouse gases, organic matter, temperature

## Introduction

The paramo is a high mountain ecosystem in the humid tropic, it is located in the Andes, the Afroalpine zone, Indonesia and Papua New Guinea (Buytaert et al., 2011). This ecosystem has a cold and humid climate, with high amount of sunlight and cloudiness, its temperature gets an anual average of 10 °C at 3000 m a.s.l. and reaches 0 °C at 4600 m a.s.l. (Llambí et al., 2013). Climate conditions in this region are variable, so that, the daily thermal amplitude ranges between 10 and 15 °C in the air and in clear days it reaches 50 °C in the soil surface (Llambí et al., 2013), while precipitation ranges between 700 mm to 3000 mm/year (Llambí et al., 2013). Despite climate conditions, there is a high biological diversity and endemism, approximately 3400 species of vascular plants inhabit the paramo of South America and 60% are endemic (Luteyn, 1999; Rangel Churio, 2000).

Paramo is considered as a carbon sink, it can store a higher quantity of carbon per hectare than tropical forests (Hofstede et al., 2014). It accumulates between 119 and

397 tons per hectare (t/ha) in 0 to 40 cm depth, (Castañeda–Martín and Montes–Pulido, 2017) meanwhile bofedales show an approximate accumulation of carbon of 30 kg m<sup>2</sup> (Segnini et al., 2010).

In addition to carbon storage in mineral soils, there is also accumulation of organic matter in peat bogs (Hofstede et al., 2014). In the north of Ecuador, it was estimated the average organic matter quantity in two peat bogs is 1282 t/ha (Hribljan et al., 2016), with an accumulation of 4.6 t/ha/year (Chimner and Karberg, 2008). Moreover, paramo vegetation contributes with fresh organic matter to soil, which means about 6 to 13 t/ha/year (Escobedo–Urquiza, 1980).

On the other hand, despite the importance of paramo through supplying environmental services such as water provision, climate regulation and carbon accumulation in soil, it is one of the more vulnerable terrestrial ecosystems to global climate change (Buytaert et al., 2011; Ruiz et al., 2008). It is found within alpine life zones that are highly sensitive to climate change because its distribution has been closely related to temperature and precipitation patterns (Cuesta et al., 2017). Likewise, if high mountain ecosystems lose humidity and the annual average temperature gets higher, it would cause an increasing conversion of organic matter into atmospheric carbon, which would favor climate change conditions (Buytaert et al., 2011; Jones et al., 2005).

In the same way, an increasing environmental temperature would augment the evaporation and evapotranspiration, altering the precipitation patterns (Arnell, 1999), which could cause a deficit in water supply to populations that depend directly on water from the paramo, like Quito and Bogotá (Buytaert et al., 2011).

In the Tropical Andes region, environmental temperature has shown an increasing trend of 0.11 °C/decade from 1939 to 1998 and 0.34 °C/decade from 1974 to 1998 (Buytaert et al., 2014). Regarding precipitation, changes have not been significant in all the region (Vuille et al., 2003). Nevertheless, records from weather stations indicate higher precipitation levels for Ecuador, but lower levels Peru and Bolivia (Buytaert et al., 2014).

The aim of this paper is to comprehensively review the state of knowledge of decomposition and climate change in paramo ecosystems to understand the consequences on ecological processes, and to obtain ideas to develop strategies to mitigate the effects of climate change.

## **Decomposition and climate projections**

Climate projections for the Andean Region show an increase in the average temperature up to 5 °C on the eastern flank of Ecuador and Peru (Herzog et al., 2012). Precipitation has a mixed pattern: increasing in the eastern and western flanks and decreasing in the inter Andean region up to 15% (Vuille et al., 2008; Urrutia, 2008; IPCC, 2013; Kirtman et al., 2013)

Predictions of global climate models and regional models for the Andean region have a high range of uncertainty due to lack of meteorological stations at altitudes above 3000 m a.s.l. (Buytaert et al., 2014). However, these projections are important to analyze the effects that climate change could have on the stability of ecosystems, environmental services and ecological processes (IPCC, 2007), especially because climate change has the capacity to alter physical and biological processes, threatening survival of endangered species (Carroll et al., 2015). For example, many studies have

focused on assessing the influence of climate change on certain species, and some results suggest that climate change conditions could lead to changes in communities composition, populations declines, range shifts, changes in relative abundance and high extinction risks (Gillings et al., 2015; Bush et al., 2016; Wang et al., 2016; Dalamsuren et al., 2017; Pecl et al., 2017; Urban, 2015).

Decomposition comprises physical and chemical processes that allow the reduction of macromolecules into their essential components (Aerts, 1997) generating CO<sub>2</sub> and soluble forms of nutrients that can be recycled in plants and other organisms (Cronan, 2018). Most of the organic matter that is involved in this process in terrestrial ecosystems are derived from plants (leaf litter, stems, root exudates) (Carter et al., 2007), while influential factors are: weather, chemical composition of leaf litter and soil organisms (Coûteaux et al., 1995; Aerts, 1997, 2006).

Concerning climate, temperature and soil moisture (commonly referred to as climate decomposition index) have shown to be the best predictors of decomposition rates (Parton et al., 2007)), they can slow or accelerate organic matter decomposition (Davidson and Janssens, 2006; Coûteaux et al., 2002).

As shown, it is evident that decomposition is different in every ecosystem (Zhang et al., 2008; Djukic et al., 2018). This was verified by assessing decomposition rates in three regions of the planet: Tropical, Temperate and Mediterranean, the average values obtained per year were 2.33, 0.36, 0.35 respectively, showing that in humid tropics the decomposition rate is higher than in the temperate and Mediterranean zones (Aerts, 1997).

Regarding chemical composition of organic matter, leaf litter quality has a significant and predictable influence on the temperature sensitivity of organic matter decomposition (Fierer et al., 2005), besides, it is also important during decomposition phases due to its effects on humus formation (Coûteaux et al., 1995). Likewise, certain plant species have low decomposition rates compared to their high lignin content (Zhang et al., 2008) or presence of polyphenols that inhibit degradation (Hättenschwiler et al., 2005).

Although bacteria and fungi are the main decomposer organisms, macroinvertebrates also play a fundamental role, starting the process of litter crushing (Ulyshen, 2016). While more organisms participate in degrading organic matter, an increase in the rate of decomposition is generated (Smith and Bradford, 2003; Wall et al., 2008).

Given the sensitivity of decomposition to climatic conditions, it is understood that global warming will increase litter decomposition rates, through direct effects and through indirect effects on leaf litter quality and soil organisms (Aerts, 2006).

## **Organic matter decomposition in paramo ecosystems**

Decomposition process in paramo ecosystems is mainly limited by atmospheric temperature that shows a high daily variation (temperature differences higher than 20 °C between night and day are common) (Hofstede et al., 2014). On the other hand, in paramo ecosystems with volcanic origins, an important factor is the presence of vesicles that organic matter generates with aluminum from volcanic ashes, turning into chemical complexes that are resistant to organisms degradation (Hofstede et al., 2003, 2014; Bottner et al., 2006).

As mentioned before, although bacteria communities are important for decomposition (Bottner et al., 2006; Pansu et al., 2004), invertebrates also play an

important role in the disintegration of organic matter (Ulyshen, 2016), its diversity is associated with the presence of vegetation (Ewers et al., 2015) and, richness of soil fauna together with climate are associated with decomposition rates globally (Wall et al., 2008).

Concerning leaf litter quality, decomposition process in paramo do not depend on lignin concentration. As paramo vegetation is mainly composed by rosettes, cushions, shrubs and herbs (Ramsay and Oxley, 1997) it is not woody, then its lignin content would be low (Coûteaux et al., 1995). Nevertheless, some species contain aromatic resins that decrease the rate of decomposition (Smith, 1981).

Several studies have analyzed decomposition processes in High Andean ecosystems focusing research in: 1) the effect of human activities on decomposition (Jiang et al., 2015; Ossola et al., 2016; Urbina and Benavides, 2015), 2) influence of altitude in organic matter decomposition (Coûteaux et al., 2002; Röderstein et al., 2005) and 3) factors that influence on organic matter decomposition (Bottner et al., 2006; Pansu et al., 2004, 2007; Ibrahim et al., 2015; Martinez et al., 2007; Pinos et al., 2017).

### **Climate change and organic matter decomposition**

It is expected that in this century, the increasing CO<sub>2</sub> concentrations and other greenhouse gases in Earth's atmosphere cause warmer surface temperatures and changes in precipitation patterns (IPCC, 2013). These environmental changes could affect the carbon cycle, modifying the function and ecosystem services (Dukes et al., 2005).

In order to determine the influence of climate change on ecosystems, models have been generated to simulate the response of the decomposition process to climate change, which have made it possible to determine that an increasing atmospheric temperature will produce a decrease of 54 gigatons (Gt) in the global carbon stock of the soil for 2100 (Jones et al., 2005).

In addition, some studies have shown the influence of climate change on the decomposition process, so that, it was determined that the increase in soil temperature accelerates the decomposition process in Arctic soils (Robinson et al., 1995), while in other study, researchers determined that the decomposition process is limited by moisture in the xeric zones and in the mesic zone it is determined by temperature (Shaw and Harte, 2001). On the other hand, a research using experimental microcosms, determined that the change of climatic conditions in a short term (from days to decades) strongly influences the decomposition process of litter (Strickland et al., 2015).

### ***Climate change and organic matter decomposition in Andean paramos***

In the Tropical Andes, atmospheric temperature near surface has increased significantly in the last 70 years (Vuille et al., 2008). A regression analysis with ordinary least squares indicates a warming of 0.10 °C/decade and a general temperature increase of 0.68 °C since 1939 (Vuille et al., 2008). Furthermore, it is suggested that in this century, in a scenario with a balanced use of fossil fuels and energies of non-fossil origin (scenario of A1B emissions), the temperature for Tropical Andes region will probably vary from <+ 1.60 °C to >+ 2.61 °C, exceeding the threshold of natural climatic variability (+ 1.78 °C) (Ruiz-Carrascal et al., 2017).

In the case of precipitation, there are no reports of increasing or decreasing patterns at a regional levels between 1955 and 1994 (Vuille et al., 2003). For the period 2071–2100 in a scenario of A1 emissions (rapid economic growth at global level, a maximum

of the world's population by the middle of the century and a rapid introduction of new and more efficient technologies) precipitation along the Andes would present a mixed pattern of increase and decrease that goes from –50 to 250% (Urrutia, 2008). In general terms, it is projected that for the second half of the 20th century, rainfall will decrease in the outer tropics and increase in the interior tropics (Urrutia, 2008; Vuille et al., 2008).

According to climatic projections for the Andean Region (10°–20°S) (Herzog et al., 2012), with a high population growth (scenario of A2 emissions), an increase in average temperature and precipitation would occur by the end of the 21st century, for example, on the western flank of the northern Peru, the increase in rainfall would be up to 70%, while in the Inter Andean region of Colombia a decrease of up to 15% will occur; and an increase of 5 °C of temperature is projected in the eastern flank of Ecuador and Peru (Herzog et al., 2012).

In the Fifth Report of the Intergovernmental Panel on Climate Change (IPCC) results of projections for an immediate climate change (Period 2016–2035 regarding 1986–2005 in RCP4.5 scenario comparable with B1) in the Andean Region suggest an increase in temperature of up to 1.5 and an increase in precipitation of up to 10% (IPCC, 2013; Kirtman et al., 2013).

An eventual change in the temperature and humidity of the paramo soil would lead to a modification in decomposition processes. It is necessary to consider that high Andean ecosystems would be more sensitive than the humid tropical forest in conditions of increasing temperature, with a trend to increase the rate of decomposition, therefore carbon sink ecosystemic services would be affected. In addition, it is important to mention that it is unknown how microbial communities would participate in different climate change scenarios (Hofstede et al., 2014).

While preparing this document, a considerable amount of information about the impact of climate change on soil and biodiversity was found. However, in the few investigations found about the effect of climate change on the decomposition process in the paramo (*Appendix 2*), it was determined that the increase in atmospheric temperature accelerates decomposition rates.

Climate change in the Andean Region will increase decomposition and mineralization rates up to 10% (Salinas et al., 2011). In situ studies through an altitudinal gradient, have allowed to project the changes of climatic conditions, being able to determine that the decomposition rate in the Andean paramo will be influenced by an increase in the air temperature (Espín Meneses, 2012). Furthermore, even if atmospheric temperature increases, when humidity decreases, decomposition rate decreases too, it happens not only due to its direct incidence on degradation process but also because it alters abundance and richness of decomposing organisms (Looby and Treseder, 2018).

## Conclusions

Despite the importance of decomposition process in the functioning of ecosystems and although since 1939 there have been alarming reports of a general increase in temperature of 0.68 °C for Tropical Andes region, there are few studies about the influence of climate change on decomposition in paramo areas, in other words, knowledge about this issue is currently scarce.

Decomposition process at biomes scale is controlled by climate, then climate change can directly affect the functioning of ecosystems. Studies about this issue mention that

the rate of decomposition increases with higher temperatures (only when humidity is maintained or increased), then an increase of 1 °C in atmospheric temperature could cause the decomposition rate to increase by up to 10%.

Projections suggest that in this century, paramo areas will have constant humidity and increasing temperatures exceeding 2 °C. According to this climate scenario, the rate of decomposition would increase, causing the carbon accumulated in the organic matter of the soil to be emitted back into the atmosphere

Exploring studies about the effect of climate change in decomposition rates in paramo ecosystems is still a challenge, we need to conduct experimental research in order to understand how ecological processes work in this ecosystem. Generating knowledge will provide people new ideas to mitigate effects of climate change for present and future scenarios.

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## APPENDIX

### *Appendix 1. Studies about decomposition process in paramo ecosystems*

Authors	Year	Title	Conclusions	Decomposition %
Hofstede	1995	The effects of grazing and burning on soil and plant nutrient concentrations in Colombian paramo grasslands.	There is greater decomposition in sites with high affectation by grazing and burning than in sites without disturbances.	In areas without disturbance, litter loss is up to $11.3 \pm 4.64\%$ per year. While in areas exposed to livestock and fire, the decomposition rate is $34.3 \pm 8.03\%$ per year.
Chapela et al.	2001	Ectomycorrhizal fungi introduced with exotic pine plantations induce soil carbon depletion.	Paramo soil with <i>Pinus radiata</i> plantations contain less carbon than paramo grassland. It is caused by the introduction of ectomycorrhizas in the roots of the pines.	The soil of the pine plantations of 10 to 20 years, show 30% less C than soils of pasture paramos.
Coûteaux et al.	2002	Decomposition of standard plant material along an altitudinal transect (65–3968 m) in the tropical Andes.	Decomposition rates decrease along with decreasing temperatures (while altitude is higher).	Five altitudes were assessed: 95, 165, 780, 1800, 3400 y 3968 m a.s.l., carbon loss percentage in the first year was 78.7, 76.6, 67.5, 62.9, 40.4 and 42.8 respectively.
Sarmiento and Bottner	2002	Carbon and nitrogen dynamics in two soils with different fallow times in the high tropical Andes: indications for fertility restoration.	In an agricultural area of the Andean region above 3000 m a.s.l., decomposition of straw in a restored soil is significantly faster than in a degraded soil.	Soil carbon loss was expressed as the initial percentage of $14C$ added to the soil (mineralized). The percentage of mineralization of $14C$ after 12 weeks of incubation was 43.9% in the restored soil and 42.9% in the degraded soil.
Pansu et al.	2004	Comparison of five soil organic matter decomposition models using data from a $14C$ and $15N$ labeling field experiment.	The best model of organic matter decomposition of soil (MOMOS) uses kinetic constants: three entries of microbial biomass MB and two MB outputs mortality and respiration constants. This model significantly improved the predictive quality and robustness of MB- $14C$ and - $15N$ predictions.	In 720 days, 80% of $14C$ was lost in the analyzed samples. This decomposition percentage was obtained in the five models of soil organic matter decomposition.

Röderstein et al.	2005	Above-and below-ground litter production in three tropical montane forests in southern Ecuador.	Decrease in temperature while altitude increases, influence the carbon cycle of montane forests. The decrease in temperature along the slope affects decomposition.	The litter mass decreased to less than one third ( $862$ to $263 \text{ g m}^{-2} \text{ y}^{-1}$ ) with increasing altitudes ( $1890$ m to $3060$ m). While litter production of fine roots increased in an approximated factor of four ( $506$ to $2084 \text{ g m}^{-2} \text{ y}^{-1}$ ).
Bottner et al.	2006	Factors controlling decomposition of soil organic matter in fallow systems of the high tropical Andes: a field simulation approach using $14 \text{ C}$ - and $15 \text{ N}$ -labelled plant material.	The relation between $\text{C}$ and $\text{N}$ is determinant in decomposition. If the $\text{C}:\text{N}$ relation in the plant material increases, the decomposition rate decreases and the mortality of the microbial biomass increases.	For $\text{N}$ -rich plant material ( $\text{N} + \text{treatment}$ ), the total of $14 \text{ C}$ remaining at the end of the experiment was similar in the Gavidia paramo and in Puna de Patcamaya: $25\%$ of the initial $14 \text{ C}$ .
Pansu et al.	2007	Modelling the transformations and sequestration of soil organic matter in two contrasting ecosystems of the Andes.	The dynamics of $14\text{C}$ and $15\text{N}$ were very different in the two systems. In the puna, the transformation processes stop during the long dry periods, although the annual total mineralization is greater than in paramo.	In dry puna, the $66\%$ of the $14\text{C}$ initially added was mineralized during the first wet season (first $120$ days). Subsequently, the mineralization was almost paralyzed until the end of the dry season (on day $400$ ), then $73\%$ of the aggregate $14\text{C}$ was mineralized after the second wet season (on day $500$ ) and $75\%$ on day $690$ after the first rain that followed the last long dry period. In humid paramo, only $42\%$ of the $14\text{C}$ added was mineralized during the initial phase of the process, then mineralization progressed slowly, until approximately $65\%$ of the $14\text{C}$ was mineralized after $1$ year, and the $75\%$ after $2$ years.
Martinez et al.	2007	Succession pattern of carrion-feeding insects in Paramo, Colombia.	The succession of scavenger insects can be an indicator of the state of decomposition and the time elapsed after an organism death.	After $83$ days, $83\%$ of the initial weight of <i>Sus scrofa</i> corpse had been lost. Five stages of decomposition were identified with indicator species: <i>Calliphora nigribasis</i> in the fresh

				stage; <i>Compsomyiops verena</i> in the swollen stage; <i>Compsomyiops Bolivian</i> during active decomposition; <i>Stearibia nigriceps</i> and <i>Hydrotaea</i> sp. during the advanced decay and <i>Leptocera</i> sp. for dry remains.
Garrido	2011	Study on radial growth, exchange and leaf decomposition of three <i>Polylepis</i> species ( <i>Rosaceae</i> ) in two locations of the Ecuadorian Andes.	There is a highly significant difference among species. <i>Polylepis reticulata</i> had the least decomposition, attributed to climatic conditions as soil moisture and temperature, since they are better predictors of decomposition than quality of its organic matter.	The global average for the remaining biomass percentage of leaf decomposition is 75.44%. <i>P. reticulata</i> shows a lower decomposition with a mean of $86.67 \pm 7.015\%$ Standard deviation (D.E.), <i>P. pattern</i> shows an average of $75.809 \pm 12.183\%$ D.E. and <i>P. incana</i> had a greater decomposition with an average of $63.83 \pm 16.467\%$ D.E.
Ibrahim et al.	2015	Modelling carbon turnover through the microbial biomass in soil.	Comparison of predictions with collected data in the field showed that the model is capable of simulating transformations and movement (plant-soil-atmosphere) of the carbon depending on the parameters previously defined	The predictions of the model showed a higher microbial content of C and a higher microbial respiration activity in the wheat plots than in vean plots. The metabolic coefficient ( $\text{mg CO}_2/\text{g MB C}$ ) after 9 months was 0.04 in wheat and 0.025 in bean.
Urbina and Benavides	2015	Simulated small scale disturbances increase decomposition rates and facilitates invasive species encroachment in a high elevation tropical Andean peatland.	Decomposition rate in soil surface (0-10 cm) triples in fertilized soils with physical disturbances in comparison with the control (soil without additions of foreign materials or physical disturbances).	Decomposition rate in the control was $0.09 \pm 0.001$ and in the plots with fertilized soils with physical disturbances was $0.25 \pm 0.005$ .
Pinos et al.	2017	Leaf litterfall and decomposition of <i>polylepis reticulata</i> in the treeline of the Ecuadorian Andes.	Temperature was one of the main regulators for decomposition rates of litter. Humidity was not controlled, then it is not a limiting factor in decomposition.	Decomposition rate of litter of <i>Polylepis reticulata</i> was $0.38 \pm 0.02$ per year. The study was conducted in an altitudinal range of 3700 to 3900 m a.s.l.

**Appendix 2.** *Studies about the effect of climate change in decomposition process in paramo ecosystem*

Authors	Year	Title	Conclusions	Decomposition %
Salinas et al.	2011	The sensitivity of tropical leaf litter decomposition to temperature: results from a large-scale leaf translocation experiment along an elevation gradient in Peruvian forests.	When samples were grouped between species and elevations, soil temperature explained 95% of the variation in the rate of decomposition, but no direct relation with soil humidity or precipitation was observed.	Heating of 0.9 °C in the last decades could have increased decomposition and mineralization rates of nutrients by 10%.
Espín	2012	Altitudinal patterns of litter decomposition in two paramo localities with different climatic regimes.	Using an altitudinal gradient to outline possible in situ scenarios on climate change is valid. It is useful to determine that there is a strong relation between temperature and decomposition rate in the Andean paramo.	Decomposition rates of litter could increase up to 5% per year with every 1 °C additional average diurnal temperature.
Salcedo	2014	Effects of the increasing temperatures and fires on Mesofauna (Arthropods) of the Soil and the Decomposition of Litter in a paramo Ecosystem in the North of Ecuador.	In a cold ecosystem such as paramo, an increase in temperature could be expected to determine greater decomposition of litter; however, the results of the study showed an opposite pattern, perhaps as a result of a decrease, at least temporarily, in the moisture content of the ground.	Decomposition rate in the treatments that were heated with cameras (which increased the temperature between 0.89 °C and 2.06 °C in the day and between 0.66 °C and 0.86 °C at night) They were between 3 and 4% slower than treatments that were not heated with cameras. The treatment with the slowest decomposition was camera/burning (54.5% ± 1.38), while the highest decomposition was recorded in the plots with the control treatment (49.7% ± 1.2).
Looby and Treseder	2018	Shifts in soil fungi and extracellular enzyme activity with simulated climate change in a tropical montane cloud forest.	Fungi abundance and alpha diversity increased significantly with warmer temperatures and drier conditions. Concerning composition of fungal community, it showed a change with increasing temperatures	With a 4 °C increase and 20% of humidity decrease, fungal abundance and richness grew in 50%.

			<p>(<math>F = 4.31</math>, <math>R^2 = 0.170</math>, <math>P &lt; 0.001</math>) and decreasing humidity (<math>F = 4.30</math>, <math>R^2 = 0.170</math>, <math>P &lt; 0.001</math>). Alterations in the composition of the community was associated with changes in the richness of certain fungal phylum. There was a general increase in Ascomycota richness with warmer temperatures and drier conditions. While, the richness of Cryptomycota decreased in translocated soils to warmer and drier conditions.</p>	
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