Chapter 23
Humic Substances Formation as a Result of Biogenic-Abiogenic Interactions in Epiphytic Structures of the South Vietnam Tropical Forest

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Abstract There are a number of ways to implementation the epiphytic biogenic-abiogenic interaction in plant communities. Epiphytic plants form a special type of organic or organo-mineral substrate—suspended soils. This study is devoted to the investigation of the biogenic-abiogenic interactions in epiphytic formations and characteristic of the suspended soils, which are formed in them with special reference to the assessment of stabilization rates and structural composition of humic acids in the suspended soil in tropical forests of South Vietnam. General properties of the soil and the elemental composition of suspended soils were determined, and the humic substance chemical composition was evaluated using solid state 13C-NMR. The soils formed by epiphytes show a positive correlation in the isotopic composition of nitrogen with epiphyte tissues and to a greater extent with forophyte tissues and, probably, take part in their nitrogen nutrition, concentrating zoogenic nitrogen due to ant presence. The most comparable soil type in terms of organic matter composition is Cambisols from humid forests of subboreal and subtropical zones. The results we obtained are consistent with the concept of soil organic matter stabilization: the proportion of aliphatic compounds in the component composition in bulk organic matter is higher than in humic acids, isolated from soils investigated. Thus, it can be concluded that in suspended soils soil organic matter stabilization processes active and expressed in formation and accumulation of humic substances.

Keywords Soils · Organic matter · Stabilization · Epiphytic formations · Epiphytic soils · Suspended soils

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23.1 Introduction

The term "suspended soils" has become more common in the literature on primary soil formation in the investigations of the tropical ecosystems in recent years. Suspended soils are a presented by a complex of mineral particles and grains and organic matter dead remnants and living tissues that has not undergone the full detritization and decomposition process and has not turned into soil organic matter in terrestrial environments (Shaw 2013). This type of organo-mineral interaction is considered as under investigated in modern soil science and terrestrial ecology. The formation of suspended soils normally happens if organic matter does not enter the litter (topsoil forest floor) at the same time, but accumulates on the surface of the obstacles: in cracks, on branches, in tree bark, and in epiphytic associations, etc., which temporarily retain organic matter from falling on the soil surface (Lindo and Winchester 2006). This transitional accumulation of the organo-mineral structures results in creation of soil like bodies, formed not on common parent material of the terrestrial ecosystems but in the intermediate tier of some forests typical for tropical climatic belt. Such soils can exist for a long time in the form of undercomposed or slightly decomposed organic matter; stabilized by various types of epiphytes (this stabilization could be physical of chemical, depending on the degree of organic matter transformation and the presence and spatial density of living organic tissues in epiphytic suspended formations). Suspended soils in the forest canopy experience large differences in temperature and humidity than in the normal forest litter, located of the mineral or organo mineral soil surface (Bohlman et al. 1995), and the decomposition rate of organic matter in the canopy may be different (Lindo and Winchester 2007). Thus, the slower decomposition of organic matter under the conditions of "air soils" or suspended soil-like formations was revealed in comparison with experimentally designed soils in experiment of the decomposition of cellulose patches in soils (Nadkarni 1986). This fact indicates completely different geochemical regime if one compare geochemical and oxidation-reduction regime in soils of norms superficial environments of terrestrial ecosystems and suspended soil of air—trees environments of the tropical forests.

Epiphytes have implemented various adaptations to their characteristic way of life in the evolution. The complicated organization of the tropical ecosystems in a vertical scales results in formation of edaphone and aerophytone layers or tiers with evident and strong differentiation of the microenvironments quality and conditions. Part of the epiphytes went along the way of xeromorphosis of the axial organs and roots, some developed various morphological devices for storing and/or trapping water and litter (Benzing 1990). The latter form the biomorphological group of accumulative epiphytes (Eskov 2012). Plants belonging to this group solve the problem of moisture deficiency and mineral nutrition by trapping and holding litter and organic debris, mutualism with insects, and the formation of water reservoirs. The general direction of their adaptations is the same: it is the formation of various devices to facilitate the existence of the accumulation of organic litter and water (Eskov 2012). Thus, complex biogenic-abiogenic interactions are formed, ensuring the formation of new ecological niches in the tropical forest canopy.

Accumulative epiphytes have xeromorphosis of leaves and stems (or rhizomes) in varying degrees. But their roots, as a rule, are much less adapted for drying than in typically xerophilic epiphytes. This is due to the fact that representatives of this group are characterized by the accumulation in the process of ontogenesis of various kinds of quasi-soil substrates, permeated by their roots. The formation of such "suspended" soils is subject to somewhat different laws than the processes of "normal" soil formation in tropical conditions.

The role of suspended soils in the circulation of organic substances and biophilic elements is underestimated. For some soils, in particular organogenic, Tolchelnikov (1985) introduced the term "degenerate" soil formation. During it, in particular, the role of one or another factor of soil formation (in this case, the soil-forming rock) decreases, which excludes the possibility of their functioning as soils in the ecosystem. There is also the concept of soil as an element of the "ecosystem of a single plant" (Chertov 1983), but the actually suspended soils accompanying epiphytic colonization in the tropics remain poorly understood.

Soil fauna is present in suspended soils, for example, mites (Lindo and Winchester 2007) and springtails (Shaw 2015). The process of settling the tree crowns of non-flying fauna is poorly understood, but presumably involves migration along the bark of the tree (Shaw 2015) or transfer on the mineral particles surface by wind.

Thus, suspended soils are an interesting and quite informative object of study not only because of the not traditional process of soil formation, but also because they represent an important factor in the conservation of biodiversity of the "epiphytic biocenosis". The species richness and species composition of ants depends on the size of the epiphyte and the presence of suspended soil (Darocha et al. 2015). It is noted that the biomass of the inhabitants of suspended soils is 20 times higher than that in the most habitable soil horizon (Sergeeva et al. 1989). In several "nests" of the *Asplenium nidus* L. species, collected from three habitats in Vietnam, 150 species of invertebrates were found (Sergeeva et al. 1997).

It was established that, for accumulative epiphytes, various ways of suspended soil accumulation, formation and differentiations of are characteristic. In cursive epiphytes, soils form under the curtain itself, the main way of soil formation is accumulation of in situ material. Very often, ants that play a certain role in the genesis and origin of suspended soil settle in the clump of an epiphyte (Eskov 2013; Eskov and Dubovikov 2015). In the case of "nesting" epiphyticism, the accumulation of litter is carried out by a funnel of leaves, and the growth of the roots, which forms a powerful soil clot around the root system, visually resembles a bird's nest located in the air stands, stabilized between the steams and roots of the current forest stands. "Staple" epiphytes use a similar mechanism, forming funnels for collecting the forest floor remnants and rainwater precipitation using specialized leaves-brackets which play an important role of organic matter accumulation in the state of suspended soils, located permanently in air.

This functional role of the "brackets accumulators" is strictly related to the genus *Drynaria*. The role of "brackets" is played by sterile, solid, hard fronds of particular morphology, the tissues of which die early, but the fronds remain on the plant for many years. Root clod mass in "bracket" epiphytes is less than in "nested" ones. Thus, the measured mass of the "nest" (substrate + roots) for *Asplenium nidus* at the end of the dry season was 5099 g, and the leaves 958 g; for "staple" epiphyte *Drynaria laurentii* (Christ) Hieron. with a total mass of 938 g, the mass of the roots and humus was only 222 g (Walter 1968). On the whole, nested epiphytes are capable for accumulating up to 30–40 kg of organic substrate of dead organic remnants per specimen or standing tree and within the community up to 277.9 kg/ha (Pocs 1976). The latter estimate is likely to be greatly underestimated. It is described that in the undisturbed forest the number of nesting epiphytes can reach 600 ind/ha with an average mass of "nest" of 3–5 kg (Zonn and Lee 1958). A large mass of suspended soil very seriously changes the water supply of epiphytes and external climatic conditions. The ability to retain water in nesting epiphytes (water holding capacity), depending on the morphology and specificity of nesting web, ranges from 45.4 to 334.9% relative to their dry weight (Pocs 1976). Even in the dry season, the moisture content of epiphytic substrates is 2.5 times higher than the moisture content of the topsoil horizon of local terrestrial environment (Sergeeva et al. 1989) and is close to 80%. This is caused by the interception of drip condensate that settles at night in the crown and practically does not reach the ground (Panfilov 1961).

In some cases, nested epiphytes form impoundment roots, they are special additional (or lateral) roots with negative geotropism, which serve as a "brush" in which litter is stuck (Benzing 1996). Nested epiphytes with such roots, as well as other devices for water and litter retention, were given the stable name "trash-basket" (Benzing 1990). The physiological cause of negative geotropism is obscure. However, in the literature there are data indicating the dependence of the formation of such roots on the level of insolation (Werckmeister 1971).

Actually, nothing is known about the anatomical structure of these roots and their growth. We have published a study of various biological features of the accumulation and formation of suspended soils (Eskov et al. 2017). We also investigated a number of properties of the suspended soils. Special attention is paid to the isotopic composition of nitrogen and carbon in various parts of epiphytic ecosystems, as a marker of their trophic status. It is known that nitrogen nutrition of woody plants of tropical ecosystems can be associated with the presence of ants (Pinkalski et al. 2015), and epiphytes can receive up to 30% of nitrogen from their livelihoods (Treseder et al. 1995). A high content of ^{15}N is noted in the tissues of ants, like other animals (Vanderklift and Ponsard 2003). On the other hand, many terrestrial (Bone et al. 2015) and epiphytic (Qiu et al. 2015) orchids, as well as epiphytes of other families, are characterized by CAM photosynthesis (a variant of organic acid metabolism characteristic of succulent plants) (Zitte et al. 2008). The difference in carbon isotopic composition between C3 plants (to which the forophytes belong) and C4 or CAM plants (Martin et al. 1990, 1992; Diels et al. 2004), as well as "animal" and "plant" nitrogen, allows us to understand the possible the path of migration of organic matter in the epiphytic community: from its source to the formation of a suspended soil in nesting epiphytes clods.

Thus, the aim of our research was the study of biogenic-abiogenic interactions in epiphytic formations, and also the characteristic of the suspended soils which are formed in them.

With the aim to implement this aim were have formulated flowing research objectives:

(1) to characterize general soil properties and elemental composition of suspended soils from various types of epiphytes and soils under forophytes from conditions of sparse savanna-like light forests of oligotrophic habitats in South Vietnam, Phu-Quoc Island;
(2) to evaluate the humic substances chemical composition using solid state 13C-NMR and to compare data obtained with those, obtained for the bulk organic matter of whole soils;
(3) to describe the organic matter stabilization process that take place in suspended soils in terms of soil organic matter structural composition.

23.2 Materials and Methods

Phu Quoc Island is located in the south-western part of Vietnam, in the Gulf of Thailand. The nearest mainland Vietnamese city, Hatien, is approximately 43 km away. Phu Quoc is considered to be the largest island of Vietnam; it is located on an area of about 575 sq. Km, stretching from its northern to southern parts for 49 km, while the width in different parts of the island is within 3–27 km. The landscape of the island is mostly mountainous. The island "99 Peaks" is another name for the island. The highest mountains are located in the north, which are gradually falling to the south. The highest point of the island is the top of Mount Chua (600 m).

Phu Quoc Island is mainly composed of sedimentary rocks from the Mesozoic and Cenozoic age, including heterogeneous conglomerate composition, layering thick, quartz pebbles, silica, limestone, riolit and felsit. The Mesozoic rocks are classified in Phu Quoc Formation (K pq). The Cenozoic sediments are classified in formations of Long Toan (middle—upper Pleistocene), Long My, (upper Pleistocene), Hau Giang (lower - middle Holocene), upper Holocene sediments, and undivided Quaternary (Q) (Thanh 2012).

The island's monsoonal sub-equatorial climate (Table 23.1) is characterized by distinct rainy (June to November) and dry seasons (December to May). The annual rainfall is high, averaging 2879 millimetres. In the northern mountains up to 4000 millimetres has been recorded. April and May are the hottest months, with temperature reaching 35 °C (Eskov 2013).

Representatives of some ecobiomorphs capable of forming suspended soils were selected for the study. Curtin-forming epiphytes, in which the curtain (in which suspended soils accumulate) itself plays an environment-forming role: *Pyrrosia longifolia, Pyrrosia adnascens*. Bracket epiphytes, forming special leaves, playing the role of funnels for collecting debris and moisture: *Platycerium grande, Drynaria sparsisora*.

Table 23.1 Climate data for Duong Dong Airport, Phu Quoc (the source is "Vietnam Building Code Natural Physical & Climatic Data for Construction" (2009))

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
Average high °C	30.4	31.1	32.1	32.3	31.4	30.0	29.5	29.2	29.2	29.9	30.3	30.0	30.5
Average low °C	22.5	23.5	24.6	25.4	25.6	25.3	25.0	24.9	24.7	24.3	24.0	22.9	24.4
Average precipitation mm	34	29	54	149	298	413	418	546	473	387	169	59	3029
Average precipitation days	5.3	3.9	5.7	11.5	19.5	21.8	22.5	24.4	22.5	21.6	13.3	6.2	178.3
Average relative humidity (%)	76.3	77.6	77.6	80.5	83.8	85.8	86.6	87.1	88.0	86.9	79.6	73.9	82.0
Mean monthly sunshine hours	251	230	255	246	196	146	151	134	139	168	208	242	2364

Nested epiphytes with ageotropic roots: *Acriopsis* sp., *Cymbidium fynlaisonianum* (Fig. 23.1). The main forophytes in these communities are: *Melaleuca leucadendra, Dipterocarpus aff. tuberculatus, Dillenia obovata* and some other species. In general, communities are poor in species composition with extremely simplified vertical structure, not close. Suspended soils are formed on lightly rolled fine quartz or quartz-microcline sands with a very low content of detrital humus.

The most problematic aspect in the suspended soil study is their phenomenology and gnoseological interpretation. The genesis and the origin most likely of all suspended soils is characterized by two important points that cannot be ignored when trying to somehow explore or classify them: (1) if the suspended soil is limited in its existence by the lifetime of the tree, (2) if they are completely isolated from the parent rock or parent materials, on which the soil-forming processes take place. Forophyte bark, in a sense, plays the parent rock role. In this context, it is appropriate formulate the question: do processes occur in suspended soil, similar to soil formation, primarily stabilization/humification of organic matter? Thus, our research was aimed at describing the processes of stabilization/humification in suspended soils that form in the roots and comas of vascular epiphytes. And find their closest analogues among terrestrial soils.

Samples of epiphytes and associated suspended soils were collected under conditions of sparse savanna-like light forests of oligotrophic habitats in South Vietnam, Phu-Quoc Island. The studied areas of savanna-like sparse formations are located near both coasts of the island, around the line between 10°16′46″ N, 103° 55′ 22.7″ E and 10° 24′ 17″ N, 104° 03′ 01.6″ E (Fig. 23.2). Soils are very poor, oligotrophic sandy loams (Eskov et al. 2017).

Soil samples were air-dried (24 h, 20 °C), ground, and passed through 2-mm sieve. Routine chemical analyses were performed using classical methods: C and N

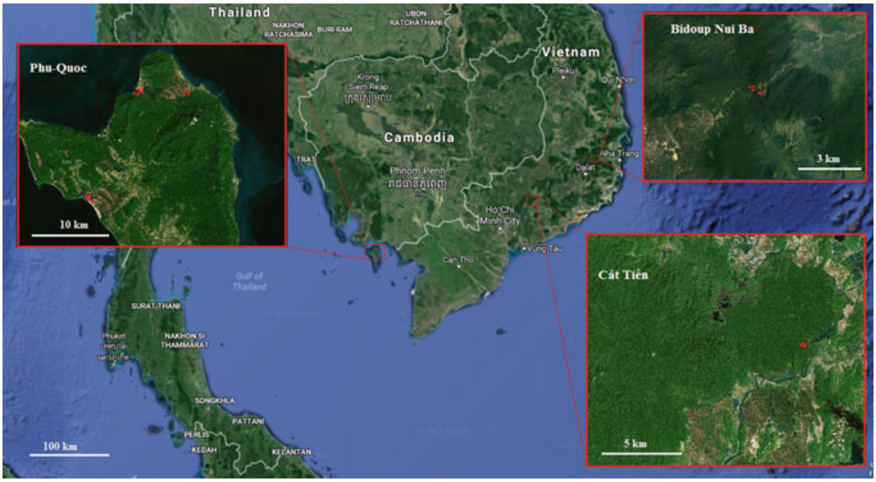

Fig. 23.1 Location of the study site: material collection plots are marked with red dots

Fig. 23.2 Studied epiphytes: epiphytic orchids—**a** *Cymbidium fynlaisonianum,* **e** *Acriopsis* sp.; epiphytic ferns—**b** *Drynaria sparsisora*, **c** *Platycerium grande,* **d** *Pyrrosia adnascens*

content were determined using an element analyzer (Euro EA3028-HT Analyzer) and pH in water and in salt (soil-dissolvent ratios 1:2.5 in case of mineral horizons and 1:25 in case of organo-mineral horizons) suspensions using a pH-meter (pH-150 M). Basal soil respiration was determined by titration of remnants of sodium hydroxide in laboratory closed chamber under humidity of soil in chamber about 60% of water holding capacity.

Humic acids (HAs) were extracted from each sample according to a published IHSS protocol (http://humic-substances.org/isolation-of-ihss-samples/) (Swift 1996). Briefly, the soil samples were treated with 0.1 M NaOH (soil/solution mass ratio of 1:10) under nitrogen gas. After 24 h of shaking, the alkaline supernatant was separated from the soil residue by centrifugation at 1516 × g for 20 min and then acidified to pH 1 with 6 M HCl to precipitate the HAs. The supernatant, which contained fulvic acids, was separated from the precipitate by centrifugation at 1516 × g for 15 min. The HAs were then dissolved in 0.1 M NaOH and shaken for four hours under nitrogen gas before the suspended solids were removed by centrifugation. The resulting supernatant was acidified again with 6 M HCl to pH 1 and the HAs were again isolated by centrifugation and demineralized by shaking overnight in 0.1 M HCl/0.3 M HF (soil/solution ratio of 1:1). Next, the samples were repeatedly washed with deionized water until pH 3 was reached and then finally freeze-dried. HA extraction yields were calculated as the percentage of carbon recovered from the original soil sample (Vasilevich et al. 2018). Data were corrected for water and ash content. Oxygen content was calculated by difference of whole samples mass and gravimetric concentration of C, N, H and ash.

Solid-state ^{13}C-NMR spectra of HAs were measured with a Bruker Avance 500 NMR spectrometer in a 3,2-mm ZrO2 rotor. The magic angle spinning speed was 20 kHz in all cases and the nutation frequency for cross polarization was u1/2p 1/4 62.5 kHz. Repetition delay and number of scans were 3 s.

In this study we collected 13-C NMR spectra not only for humic substances, but also for a bulk soil samples. This allowed us to reveal the differences in alteration degree between bulk initial soil organic matter and its organic matter of the suspended soils which faced to intensive stabilization/humification processes.

23.3 Results

Suspended soils belong to the category of organic soils or soil-like formations, although they are taken into account in any classification of soils in Russia soil taxonomy and the World Reference Base of Soil Resources (2014). Suspended soils investigated are presented buy organic accumulations, located in air baskets, formed by plants roots. The degree of transformation of organic matter on the basic of morphological identification is medium, but nevertheless some spots of soil organic remnants become deeply decayed and humified, which result in formation of gray-brownish organic matter with high gravimetric water content, The closest analog of this soil on Russian soil taxonomy are the soils from the order, belonging to the trunk of organogenic soils. The main feature of normal terrestrial organogenic soils is a «histic structure» of the horizons. IS soils investigated we can find thus Histic fragments, thus they could be classified as suspended Histosols or suspended peat-like formations.

Suspended soils should be attributed to slightly acidic (in terms of pH in water), which is characteristic of organic substrates in which the transformation of organic matter takes place. The fact that the transformation of organic matter takes place also shows a much lower pH of the salt suspension. The presence of additional absorbed acid ions is associated with the carboxyl groups of the forming organic matter of the soil. Usually, suspended soils (1, 2 samples) are more acidic than soils under the forophyte (3 sample).

The carbon content in suspended soils is much higher than in soils under the forophyte, and this probably affects their acidity. The soils under the phorophyte contain less carbon from organic compounds, as well as nitrogen. A lower content of

Table 23.2 Base characteristics of suspended and associated ground soils

Species of epiphyte from which suspended soil is collected	pH in water	pH in salt (KCl)	Skeleton,%	Basal respiration, ($mgCO_2$/100 g/day)	Specific respiration (mgC–CO_2/g Csoil per day)	C, %	N, %	C/N
Acriopsis sp.	5.5 ± 0.4	3.8 ± 0.3	0	2162.3 ± 142.2	12.9 ± 0.6	45.5 ± 0.9	0.9 ± 0.01	47.5 ± 1.6
Cymbidium fynlaisonianum	5.0	3.8	0	1860.6	12.4	41.1	1.4	27.7
Drynaria sparsisora	5.7 ± 0.4	4.1 ± 0.8	6.7 ± 8.6	1719.9 ± 632.5	6.5 ± 3.6	44.5 ± 2.5	1.3 ± 0.3	33.4 ± 7.9
Platycerium grande	5.6	4.3	0	2112	12.5	46.2	1.1	38.8
Pyrrosia adnascens	5.8 ± 0.5	3.9 ± 0.8	5.5 ± 11	1257.1 ± 561.5	33.7 ± 48.8	33.6 ± 21.6	1.1 ± 0.6	23.9 ± 11
Pyrrosia longifolia	5.3 ± 0.8	3.7 ± 1.1	3.3 ± 2.3	339.4 ± 17.8	12 ± 12.7	18.2 ± 19.7	0.5 ± 0.5	25.6 ± 11.2
Ground soils	6.3 ± 0.1	5.1 ± 0.3	0.1 ± 0.1	440 ± 165.1	52.5 ± 34.7	3.7 ± 2.5	0.2 ± 0.1	14.9 ± 6.3

Table 23.3 The groups distribution of structural carbon compounds in the composition of the soil organic matter (SOM) and humic acids (HA), %

Groups of structural carbon compounds	Chemical shifts values, ppm	The number of the soil sample					
		1		2		3	
		SOM	HA	SOM	HA	SOM	HA
Carbonyl/carboxyl/amide	220–160	11.71	15.45	12.16	14.36	12.66	14.06
Aryl-olefine	160–110	24.19	26.78	22.01	24.31	18.89	25.55
O-N alkyl	110–45	49.45	35.17	51.06	38.06	42.61	38.36
Calkyl	45–0	14.64	22.61	14.76	23.28	25.81	22.02
Calkyl/O-N alkyl		0.296	0.643	0.289	0.612	0.606	0.574
Caryl/Calkyl		1.652	1.185	1.491	1.044	0.732	1.161

organic matter in these soils was also detected by the mesomorphological method. Our study showed that in the soil under the forophyte coarse-humus material is poorly associated with the mineral part of the soil, it is not so much, and it is in the initial stages of transformation. According to mesomorphological studies in suspended soils, organic matter is more decomposed, and the mineral part in it is contained as an impurity. However, some suspended soils do not contain any impurities of dust or sand at all, while others have up to 18–22% of the mineral skeletal part (Table 23.1). The C/N ratio in the studied objects is different. So, in suspended soils, it is usually more than 30, while in soils under forophytes it averages 11–17. This is probably due to the presence of mineral forms of nitrogen in the soils under the phorophytes, while in suspended soils nitrogen is represented mainly by organic forms, and the high carbon to nitrogen ratio is provided by an elevated carbon content, which is explained by the nature of the formations themselves. Thus, it can be concluded that not only the morphological organization is different, but also the parameters of the chemical composition of the suspended soils and the soils under the phorophytes. The basal respiration of soil bodies differed both in absolute (mg of CO_2 per 100 soils) and in specific (mg—CO_2/g C of soil per day) values (Table 23.2).

The existence of biogenic-abiogenic systems (epiphyte-invertebrates-suspended soil) provides the organic matter transformation. By the 13C mass spectrometry, it is possible to determine the structural composition of organic substances (Table 23.3), which is an indicator of humification processes (Abakumov et al. 2018). In general, suspended soils are characterized by a low content of aromatic compounds (Fig. 23.3).

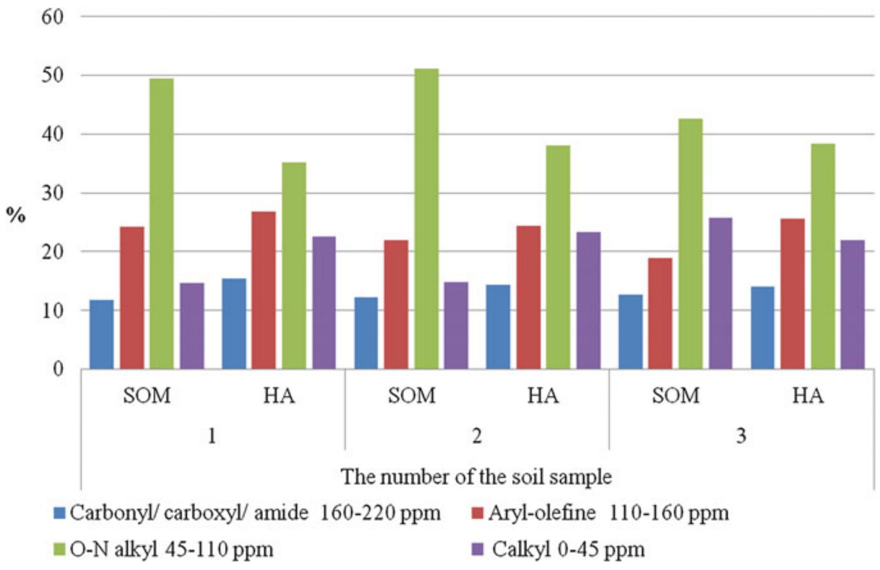

Fig. 23.3 The groups distribution of structural carbon compounds in the composition of the soil organic matter (SOM) and humic acids (HA), % in suspended soils (1, 2 samples) and soils under the forophyte (3 sample)

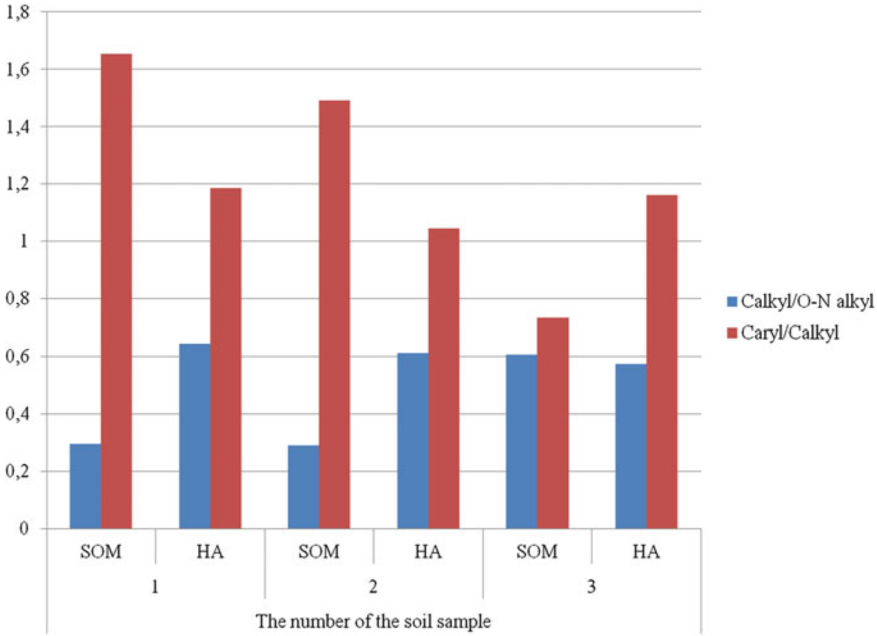

Fig. 23.4 The ratio of the structural carbon compounds in the composition of the soil organic matter (SOM) and humic acids (HA),% in suspended soils (1, 2 samples) and soils under the forophyte (3 sample)

Increasing the values of the different alkyl groups ratio (C alkyl/O-N alkyl) from 0.3 (in SOM) to 0.6 (in HA) suggests a higher degree of decomposition of the substance in the organic matter stabilization process (Baldock et al. 1997). At the same time, the opposite situation is observed in sample 3—the value of the C alkyl/O-N alkyl ratio is higher in SOM, although not significantly (Fig. 23.4). Perhaps this is due to the fact that the first two points of the research are quite closed systems (epiphyte-suspended soil), in contrast to 3 point (the soil under the forophyte). The sandy soil under the forophyte has a stronger washing mode and is better aerated, which affects the soil-forming processes, reducing the part of plant residues decomposition in these specific conditions.

The relationship between aromatic C and aliphatic C (C aryl/C alkyl) provides additional information on soil components (Mueller and Kögel-Knabner 2009). Indeed, the lower aliphatic structures decomposability dominated in sample 3 (soil organic matter), which was shown by low ratios of aromatic and aliphatic carbon. This indicates that the organic matter stabilization processes under the forphyte proceed with less intensity and in a different way, in contrast to the sites of suspended soils.

23.4 Discussion

Abovementioned data give an idea that the formation of suspended soils is an integral part of the survival strategy of a number of epiphytes. Suspended soils contribute to the mineral nutrition of epiphytes, concentrating significant portions of organic matter in crowns and giving shelter to numerous invertebrate consorts (Lindo and Winchester 2006, 2007; Rodgers and Kitching 1998; Karasawa and Hijii 2010). However, a comparison of the isotopic compositions of nitrogen and carbon of suspended soils and possible sources of their origin suggests that under the conditions of oligotrophic communities, they most likely have a zoogenic origin and are formed due to the cohabitation of epiphytes with ants (Eskov et al. 2017). The mechanisms of accumulation of organic matter in different ecobiomorphological groups are differ (Eskov et al. 2017). The study of organic matter stabilization processes in suspended soils was carried out for the first time. Samples investigated included soil from under the forophytes (mineral soil represented by samples of topsoil from the typical dry savanna landscape) and soil from savanna epiphytic formations in sparse communities that are located on the oligotrophic plains on Phu Quoc Island (South Vietnam). Our results show that the pH of the soil under the forophytes is higher than in suspended soils and that it depends on a larger amount of undecomposed organic matter compared to the mineral part in suspended soils, which causes a stronger acid reaction. This is due to the slow transformation of organic acids into humic substances. A greater amount of undecomposed organic matter compared to the mineral part in suspended soils causes a stronger acid reaction. In addition, suspended soils are less enriched with nitrogen than soils under forophytes. Basal respiration, which indicates the level of the microbial biomass activity, does not tend to change in the soils under the forophytes compared with suspended soils.

The soil under the forophytes is characterized by a greater portion of aromatic fraction and a smaller proportion of aliphatic groups. This can be explained by a higher degree of organic matter transformation in more aerated soil environments under phorophytes, where organic residues are surrounded by minerals, or are processed by termites. The content of aromatic compounds is higher than in tundra or taiga soils, but lower than in mollisols. The soils that we explored were an intermediate option between soils with a large amount and soils with a small amount of moisture. The most comparable soil type in terms of the composition of humic substances is Cambisols from humid forests of the subboreal and subtropical zones. The results of our study show that the formation of deeply moistened organic matter with a significant content of the aromatic fraction can be carried out in the process of organic matter transformation on suspended soils with a clear absence of mineral compounds or a mineral fine-grained medium in conditions of pure organic substrates. From a botanical point of view, it is worth paying attention to the fact that a look at suspended soils as soils allows us to speak of epiphytes as edificatories of their habitat In the lower tier of the tropical forest, all coarse organic matter (for example, litter or wood) is destroyed by termites and nothing like peat, leaf litter, etc., accumulates, and suspended soils remain inviolable throughout the life of the tree (Lindo and Winchester 2006, 2007; Nadkarni 1986). Is this a delicate balance in the wetting/drying mode or a specific microflora, or, finally, ants-antagonists of termites? In fact, we have—on the ground in tropical forest, organic matter always decays rather quickly, in crowns it can accumulate and persist for tens and hundreds of years (however, having fallen to the ground, suspended soils are also rather quickly utilized (Nadkarni 1986).

The main feature of soil is a presence of stabilized/humified organic matter (Kholodov et al. 2011; Lodygin et al. 2007). Our results indicated that humification as a specific way of soil organic matter stabilization occurs even in suspended air located environments of forest ecosystems (Abakumov et al. 2018) and our data are comparable to previously obtained (Abakumov et al. 2018; Eskov et al. 2017). These environments could be considered as extreme type of environments. Thus, for the extreme environments of the Antarctic was established the possibly of humification (Mergelov et al. 2018; Abakumov and Alekseev 2018). This is a reason why humification is possible in less severe conditions of the tropical environments. An accumulation of aromatic fraction could be considered as index of organic matter stabilization. In this context, increasing of aromatic carbon content in humic acids in comparison with the bulk organic matter is an evident fact.

23.5 Conclusions

Stabilization and humification are universal processes of the transformation of organic substances and the polymerization of oligomeric and monomeric molecules into supramolecules of high-molecular substances of dark color. This process is considered as a global process, carried out not only in soils and organic sediments, but also in natural waters and even in the air (Morley et al 2005; Wang 2005). Wherein study of the humification phenomena in the suspended soils of tropical forests can be discussed as undervalued in this section of science.

According to the thermodynamic concept of humification (Schnitzer 1982), thermodynamic selection of humic substances based on the selection of stable aromatic rings conjugated with carboxyls, and the aliphatic periphery decreases slightly due to mineralization. The results we obtained are consistent with this concept: the proportion of aliphatic compounds in the composition of the structural of the gross organic matter is higher than in humic acids. Thus, it can be concluded that in suspended soils humification processes is occur.

Summing data, the suspended soils have a special way of soil formation. They are a variant of the primary soils, including the mineral part, the roots of epiphytes and litter, and perform their ecological functions in the formed communities. Being in an intermediate position between the litter stuck in the crown (long-lasting organic matter) and the soil surface under the forophytes (rapidly recyclable organic matter), suspended soils provide for the transformation of organic matter and support the circulation of substances.

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References

Abakumov EV, Rodina OA, Eskov AK (2018) Humification and humic acid composition of suspended soil in oligotrophous environments in South Vietnam. Appl Environ Soil Sci 1:1026237

Abakumov E, Alekseev I (2018) Stability of soil organic matter in Cryosols of the maritime Antarctic: Insights from 13C NMR and electron spin resonance spectroscopy. Solid Earth 9(6):1329–1339

Baldock JA, Oades JM, Nelson PN (1997) Assessing the extent of decomposition of natural organic materials using solid-state 13C NMR spectroscopy. Soil Res 35:1061–1084

Benzing DH (1990) Vascular epiphytes: general biology and related biota. Cambridge University Press, Cambridge

Benzing DH (1996) Aerial roots and their environments. In: Waisel Y, Eshel A, Kafkafi U (eds) Plant roots: the hidden half. Marcel Dekker, New York

Bohlman SA, Matelson TJ, Nadkarni NM (1995) Moisture and temperature patterns of canopy humus and forest floor soil of a Montane Cloud Forest, Costa Rica. Biotropica 27(1):13–19

Bone RE, Smith JA, Arrigo N, Buerki S (2015) A macro-ecological perspective on crassulacean acid metabolism (CAM) photosynthesis evolution in Afro-Madagascan drylands: Eulophiinae orchids as a case study. New Phytol 208:469–481

Chertov OG (1983) Mathematical model of a single plant ecosystem. J Gen Biol 44(3):406–414 (in Russian)

Darocha WD, Ribeiro SP, Neves FS, Fernandes GW, Leponce M, Delabie JHC (2015) How does bromeliad distribution structure the arboreal ant assemblage (Hymenoptera: Formicidae) on a single tree in a Brazilian Atlantic forest agroecosystem? Myrmecological News 21:83–92

Diels J, Vanlauwe B, van der Meersch MK (2004) Long-term soil organic carbon dynamics in a subhumid tropical climate: 13C data in mixed C3/C4 cropping and modeling with ROTHC. Soil Biol Biochem 36:1739–1750

Eskov AK (2012) Ecophysiological classification of vascular epiphytes as a theoretical prerequisite for the formation of collections and communities of epiphytic plants in a greenhouse culture. Nat Technol Sci 4:93–98 (in Russian)

Eskov AK (2013) Epiphytic communities of tree formations of South Vietnam: analysis of the species composition and structure of sinusias depending on the degree of anthropogenic influence. J Gen Biol 74(5):386–398 (in Russian)

Eskov AK, Dubovikov DA (2015) Community of myrmecophilic epiphytes of the Kerangas Formation of the Borneo Island. Byull Mosk O-va Ispyt Prirod Otd Biol 120(4):60–69 (in Russian)

Eskov AK, Abakumov EV, Tiunov AV, Kuznetsova OA, Dubovikov DA, Prilepskij NG, Antipina VA, Kuznetsov AN (2017) Ageotropic aerial root-traps of nest epiphytes and their role in suspended soils forming. J Gen Biol 78(3):54–68 (in Russian)

Karasawa S, Hijii N (2010) Oribatid communities (Acari: Oribatida) associated with bird's nest ferns (*Asplenium nidus* complex) in a subtropical Japanese forest–a mini-review. Trends in Acarology. Springer, Dordrecht, pp 149–153

Kholodov VA, Konstantinov AI, Kudryavtsev AV, Perminova IV (2011) The structure of humic acids of zonal soils according to C-13 NMR spectroscopy data. Pochvovedenie 9:1064–1073 (in Russian)
Lindo Z, Winchester NN (2006) A comparison of microarthropod assemblages with emphasis on oribatid mites in canopy suspended soils and forest Goors associated with ancient western redcedar trees. Pedobiologia 50(1):31–41
Lindo Z, Winchester NN (2007) Oribatid mite communities and foliar litter decomposition in canopy suspended soils and forest floor habitats of western redcedar forests, Vancouver Island, Canada. Soil Biol Biochem 39:2957–2966
Lodygin ED, Beznosikov VA, Chukov SN (2007) Paramagnetic properties of humus acids of podzolic and bog-podzolic soils. Eurasian Soil Sci 40(7):726–728
Martin A, Mariotti A, Balesdent J (1990) Estimate of organic matter turnover rate in a savanna soil by 13C natural abundance measurements. Soil Biol Biochem 22:517–523
Martin A, Balesdent J, Mariotti A (1992) Earthworm diet related to soil organic matter dynamics through 13C measurements. Oecologia 91:23–29
Mergelov N, Mueller CW, Prater I, Shorkunov I, Dolgikh A, Zazovskaya E, Shishkov V, Krupskaya V, Abrosimov K, Cherkinsky A, Goryachkin S (2018) Alteration of rocks by endolithic organisms is one of the pathways for the beginning of soils on Earth. Sci Rep 8(1):3367
Ministry of Construction of Vietnam: Vietnam Building Code 2009 (2009) QCVN Natural Physical & Climatic Data for Construction 02:2009/BXD, Hanoi
Morley CP, Mainwaring KA, Doerr SH, Douglas P, Llewellyn CT, Dekker LW (2005) Organic compounds at different depths in a sandy soil and their role in water repellency. Aust J Soil Res 43:239–249
Mueller WC, Kögel-Knabner I (2009) Soil organic carbon stocks, distribution, and composition affected by historic land use changes on adjacent sites. Biol Fertil Soils 45:347–359
Nadkarni NM (1986) The nutritional effects of epiphytes on host trees with special reference to alteration of precipitation chemistry. Selbyana 9:44–51
Panfilov DV (1961) Insects in tropical forests of southern China. Moscow State University Publishing House, Moscow (in Russian)
Pinkalski C, Damgaard C, Jensen KV, Peng R, Offenberg J (2015) Quantification of ant manure deposition in a tropical agroecosystem: implications for host plant nitrogen acquisition. Ecosystems 18:1373–1382
Pocs T (1976) The role of the epiphytic vegetation in the water balance and humus production of the rain forests of the Uluguru Mountains, East Africa. Boissiera 24:499–505
Qiu S, Sultana S, Liu ZD, Yin LY, Wang CY (2015) Identification of obligate C3 photosynthesis in *Dendrobium*. Photosynthetica 53(2):168–176
Rodgers DJ, Kitching RL (1998) Vertical stratification of rainforest collembolan (Collembola: Insecta) assemblages: description of ecological patterns and hypotheses concerning their generation. Ecography 21(4):392–400
Schnitzer M (1982) Organic matter characterization. In: Page B, Miller R, Keeney D (eds) Methods of soil analysis. Soil Science Society of America, Madison
Sergeeva TK, Kholopova LB, Tien Nguyen Three, Nguyen Shung Tu (1989) Animal population and properties of "suspended soils" of tropical epiphyte *Asplenium nidus* L. Ecology 5:29–40 (in Russian)
Sergeeva TK, Kompantsev AV, Kompantseva TV, Vtorova VN (1997) Diversity of biota of "suspended" soils in the tropical forests of Vietnam (using the *Asplenium nidus* L. fern as an example). Troptsentr-98, Book 1. Biological diversity and the current state of the tropical ecosystems of Vietnam. Moscow, Hanoi (in Russian)
Shaw P (2013) The use of inert pads to study Collembola of suspended soils. Soil Org 85(1):69–74
Shaw P (2015) How high do Collembola climb? Studies of vertical migration in arboreal Collembola. Soil Org 87(3):229–235

Swift RS (1996) Organic matter characterization. In: Sparks DL et al (eds) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America Book Series 5. Soil Science Society of America, Madison, WI

Thanh TD (2012) Biển đảo Việt Nam - Tài nguyên vị thế và những kỳ quan địa chất, sinh thái tiêu biểu (Vietnamese sea and islands—position resources, and typical geological and ecological wonders). Natural Science and Technology. Hanoi (in Vietnamese)

Tolchelnikov YS (1985) On the essence of the concept of "soil" MSU Vestnik Series 17. Soil Sci (3):52–58 (in Russian)

Treseder KK, Davidson DW, Ehleringer JR (1995) Absorption of ant-provided carbon dioxide and nitrogen by a tropical epiphyte. Nature 375:137–139

Vanderklift MA, Ponsard S (2003) Sources of variation in consumer-diet $\delta^{15}N$ enrichment: a meta-analysis. Oecologia 136:169–182

Vasilevich R, Lodygin E, Beznosikov V, Abakumov E (2018) Molecular composition of raw peat and humic substances from permafrost peat soils of European Northeast Russia as climate change markers. Sci Total Environ 615:1229–1238

Walter G (1968) Earth's vegetation: ecological and physiological characteristics. T. 1. Tropical and subtropical zones: (Trans. from the German Rethyum YY and Spichkin IM (eds)). Whippers PB Progress, Moscow (in Russian)

Wang KJ (2005) Characterization of humic substances and non-ideal phenanthrene sorption as affected by clay-humic interactions. Ph.D. dissertation, University of Massachusetts

Werckmeister P (1971) Light induction of geotropism, and the control of proliferation and growth of Cymbidium in tissue culture. Bot Gaz 132(4):346–350

World Reference Base for Soil Resources (2014) International soil classification system for naming soils and creating legends for soil maps update 2015. http://www.fao.org/3/i3794en/I3794en.pdf. Access date 20 Mar 2019

Zitte P, Weiler EV, Kaderayt VV, Brezinski A, Körner K (2008) Botany. T. 2. Plant physiology. In: Chuba VV (ed) Academy, Moscow (in Russian)

Zonn SV, Lee C-K (1958) Some questions on the genesis and classification of China's tropical soils. Soil Sci 6:58–69 (in Russian)