Chapter 11
Does Humus Accumulate and Where? What Factors May Influence?

11.1 Introduction

Neither C nor N was present in the original mineral soil that existed before plants evolved, but entered the ecosystem from the atmosphere. Both C and N are macronutrients and fulfill very different functions. Carbon makes up the skeleton of the macromolecules that create a storage matrix for N and other nutrients. Nitrogen is a major nutrient that must be stored in the ecosystem, to supply plants with an even flow of mineral N. Loss of N from the ecosystem would cause the vegetation on a given plot to move to an earlier successional stage due to N limitation, and the ecosystem may need N_2-fixing organisms to restore N to its prior level.

The mechanism by which the ecosystem stores C and N depends on the structure of the litter produced by a given plant, the degree to which that litter decomposes and the transformations it undergoes during decomposition. It would be reasonable to expect that each plant species would produce litter and litter remains that would store nutrients in concentrations high enough to allow the species to survive.

Nutrient elements can be added to an ecosystem through abiotic weathering, aerosol inputs from outside the system, or through fertilization. Ecosystems have the capacity to store at least some of these added nutrients.

The microbial decomposition of plant litter is a basic process in the functioning of ecosystems, not only for the general release of nutrients to plants, but also for the buildup of stable humus and the accompanying storage of nutrients.

Humus accumulates as the stand grows and ages (Ovington 1959; Forrest and Ovington 1970; Bormann and de Bell 1981; Schiffman and Johnson 1989). In these studies, the accumulation followed a nearly linear increase with stand age. However, a model formulated to describe the linear accumulation of humus with time may be general, but lacks causality.

If we define humus accumulation and carbon sequestration rates as the increase in the amount of humus/carbon per unit area, the rates may be estimated by a summation of the recalcitrant or resistant part of the decomposing litter (Sect. 10.4.1).

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There is good support for the observation that a long-term net accumulation of humus takes place, even over millennia (Jenny 1980; Wardle et al. 1997). Such an accumulation can be predicted using the limit-value approach to humus accumulation at least for some undisturbed systems (Berg et al. 2001). The stable fraction is based on the concept of limit values (Chaps. 2 and 6) that gives the fraction of litter that decomposes extremely slowly. The level of the limit value is determined by causal factors, such as those discussed, namely concentrations of Mn, N, and AUR (Chaps. 2, 6, 10). In addition, we may have less investigated factors, one of which may be heavy metals in litter.

In Chap. 10, we discussed limit values (the stable fraction) and factors influencing the level of the limit value. We also showed that the limit value in combination with litter fall may be used to estimate carbon sequestration rates in forest stands. In the present chapter, we follow this path and investigate the growth of the humus layer. Depending on the specific measurement, we may find FH layers (the stabilized humus in the forest floor) or the FH layer plus litter (LFH). We may refer to Fig. 11.1 and call this a primary sequestration, the one that takes place on top of the mineral soil in the organic layer, for example a mor layer. We discuss this and influencing factors and intend to approach the complex of humus buildup (carbon sequestration) stepwise. Whereas we in this chapter focus on a small scale, we have devoted Chap. 12 to more large-scale and regional evaluations. This chapter aims to evaluate basic observations; what a storage mechanism for humus may mean in terms of amounts of humus stored . Of course, this is an extrapolation

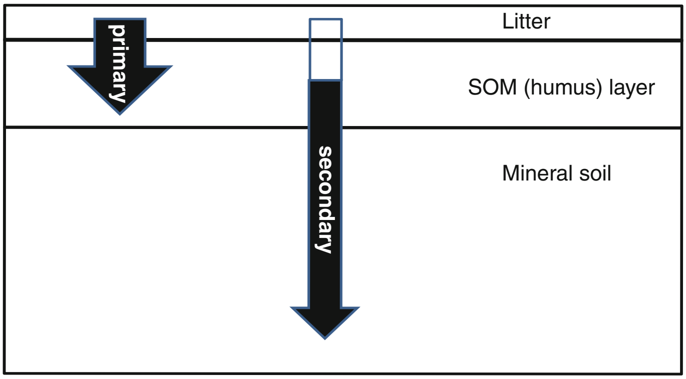


Fig. 11.1 Primary and secondary sequestration of carbon in humus and mineral soils. The arrow ‘primary’ indicates a transport of decomposing litter to the organic layers with more resistant/ recalcitrant material and into a sink for material that is in a state of primary sequestration (long-term stable), for example a mor layer. The arrow ‘secondary’ indicates a transport of soluble organic material into the mineral soil. This secondary sequestration requires that material from upper layers is solubilized and transported with water to the mineral soil where it is sequestered. It is evident that root litter will contribute to the organic matter in the mineral soil. We have taken an example from a soil with clearly different layers. The layer(s) with primary sequestration in an organic layer are also called A_{01} and A_{02} or O_e and O_a or F and H. From Berg et al. (2008)

of existing, partially empirical, data and must be regarded as a prediction that needs to be validated.

In this chapter, we focus on studies carried out on types of forest soils in which more clear and accurate quantitative determinations can be made, which means a focus on boreal and temperate coniferous forests and mor soil. For forests in these climate types, there is a reasonable amount of available data. However, whenever data are available, we have compared the results from studies of other systems.

11.2 Amounts of Humus and Increase in Organic Layers. Is There a Steady State?

The accumulation of stabilized soil organic matter is the net result of a sequence of several subprocesses. The input through litter fall, in its turn dependent on site productivity, may be seen as a first step, followed by the decomposition processes, leaving a certain fraction as stabilized residue. Once this has been formed, a necessary request is the maintenance of the long-term stability of the litter fraction.

The two groups of processes, namely those resulting in accumulation and those in decomposition as well as several subprocesses, may be ruled by different conditions and have different optima. We may measure the net result as the amount of, for example, mor humus at a given point in time or over a period, thus obtaining a net change, for example an increase (sequestration) or a loss. One interpretation of a high sequestration rate is that the main processes, either all or most of them, have close to optimum conditions.

One strong driving variable to these processes ought to be the climate, and more than two centuries ago, de Saussure (1796) expressed the opinion that difference in climate was a primary influencing factor for the variable amounts in organic matter found on and in the soil. Among other scientists, Jenny (1930, 1941) found that the geography of soil carbon is controlled by temperature and moisture. Later, Meentemeyer et al. (1985), relating measured amounts of carbon to climate, found that stored soil carbon was related to actual evapotranspiration (AET) with an optimum at an AET of c. 390 mm. Their model also included site disturbance and annual soil moisture deficit. The model was valid for moderately drained sites but did not account for local effects.

Today, there are numerous estimates of soil carbon amounts, both global ones and for specific forest systems. The amounts of soil carbon stored in the upland boreal forest (the taiga) have been estimated to as much as 1,700 Pg (1,700 Mt), corresponding to c. 50 % of the global soil carbon and c. 18 times that in the boreal vegetation (DeLuca and Boisvenue 2012). Locally, amounts have been found to range between close to none and 245,000 kg ha^{-1} (Wardle et al. 1997).

Considering such a climate dependence as observed already by Meentemeyer et al. (1985), it would be obvious that there should be relationships not only between AET and standing amounts of soil carbon but also between climatic factors and accumulation rate of C in stabilized SOM. We here refer to the net accumulation as the product of litter fall and the stable fraction of litter (primary sequestration, Fig. 11.1).

Accumulation or increases in stabilized SOM-C in, for example, humus layers have often been considered to continue until a steady state has been reached. The concept steady state has not been very clear in the context of soil carbon, although a general definition exists. Jenny (1980) discussed the concept and concluded that '…the soil organic matter regime is often viewed in short perspective as a steady-state system with inputs of C and N balancing their egress.' Suggestions have been forwarded about a regional steady state, for example for a whole country when including all possible influencing factors (Schulze et al. 1989). They suggested that the forested land of Sweden should be in a steady state as regards humus growth. However, such a statement may be difficult to confirm. Further, considering only the current humus layers, such a concept based on a whole region may need to allow rather wide fluctuations when we consider possible growth rates (Chap. 12) (e.g., Berg et al. 2009).

Organic layers may grow for millennia at least in limited areas or niches and be quite deep even in systems that are not waterlogged. Thus, Wardle et al. (1997) reported that a whole group of islands in Swedish Lapland, well protected from forest fires over a period of slightly less than 3,000 years, had developed mor humus layers to a depth of up to 150 cm. Berg et al. (1993, 2003) reported humus layers more than 1 m thick on Monte Taburno just east of Naples (Italy). Such layers have also been observed in NW Spain (B. Berg, pers. obs.). Also, in the Alps and Central European Mountains, the established concept 'Tangelhumus' (Rehfüss 1990; www.GeoDZ.com) means organic layers of up to 1 m depth. Thus, deep raw humus layers suggesting a long-term development may question the concept 'steady state' at least for coniferous forests over Europe. In the case reported by Wardle et al. (1997), growth had been continuous for close to 3,000 years (Fig. 11.2) and a highly significant relationship suggests a continued growth.

With such a growth over millennia, the concept steady state may become less interesting. We may consider the possibility that at least some ecosystems simply do not develop any kind of steady state unless factors such as wildfire may be a frequent regulating factor for humus growth. Of course, with a high wildfire frequency, for example at least every 50 years, a kind of steady state may develop, but will be broken with better fire prevention.

As regards the possible development of a steady state for some forest systems, we may consider this as being a balance between litter input, the degradability of litter, and the environmental influences on the sequestration process. Several factors influence the litter fall, litter chemical composition, and the stability of a potentially stable fraction as well as the multitude of litter species. Further, these may be combined with a variable and continuously changing environment, for example climate. One reasonable result is that we may expect several possibilities for humus layers to develop with developments following different patterns. Some seemingly extreme examples would be on the one hand more than meter-thick

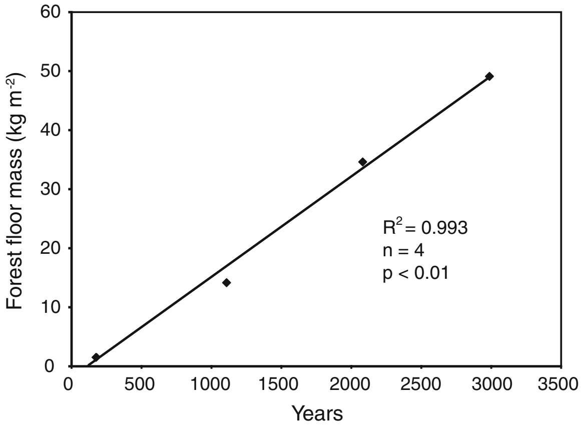


Fig. 11.2 A relationship ($R^2 = 0.993$; $n = 4$; $p < 0.01$) between the year for the latest forest fire and the accumulated humus carbon measured on isolated boreal islands. The islands were forested with Scots pine, Norway spruce, and birch spp. 50 islands were subdivided into groups according to age, with 2,984 years an average for 14 stands, 2,081 years an average for 24 stands, 1,106 years the average age for 12 stands. A 120-year-old Scots pine stand with 25 replicate samples was added. The age is that estimated since the humus layer growth started. Data from Wardle et al. (1997) and Berg and Staaf (1977)

humus layers (e.g., Tangelhumus) and on the other hand systems in which leaf litter residues never accumulate, but decompose so quickly that no organic layer is formed.

11.3 Accumulation of Stabilized Humus/Carbon in Organic Layers of Boreal and Temperate Forests

11.3.1 Accumulation with Stand Age

The purpose of this section is to show that there is a clear increase in organic-layer carbon with stand age. This has been observed by sampling both one stand over time and in chronosequences. In contrast, there are deciduous forest ecosystems that appear not to form any humus layer and just litter residues are found on the ground on top of the mineral soil after 1 year of decomposition. As mentioned above, any change in the amount of mor humus or mor humus C is the net result of several processes that both add and remove matter and we may consider any increase to be a net increase and any change a net change.

Observations in pine spp stands and chronosequences. It appears common, at least in boreal and temperate coniferous forest ecosystems that a net increase takes place in stabilized mor humus stored in distinguishable humus layers. Early descriptions of this process are those of Ovington (1959) (Fig. 11.3) and a later one is that of Schiffman and Johnson (1989). Using chronosequences of Scots pine and loblolly pine stands, respectively, they demonstrated a rapid growth of both the FH layer and the total amount of dead organic matter in the forest floor. Measurements in a chronosequence of Scots pine in central Holland (Tietema 2004) gave a continuous increase with stand age and could be described by a linear relationship (Table 11.1).

An extreme event may be one at a Scots pine site in South Germany, where no change could be detected after 22 years although a nearby site showed an accumulation of 196 kg C kg ha^{-1} year^{-1} over 30 years (Prietzel et al. 2006).

Two stands with pine at warmer sites also showed an increase in the amount of sequestered humus with stand age. Thus, a stand with loblolly pine at a subtropical climate (southeast USA) showed a clear net increase over a period of 47 years (Table 11.1). A stand with Monterey pine (NSW, Australia) under a subtropical climate also increased the SOM-C mass in the forest floor, an increase that was linear *versus* stand age and with a rate of 1032 kg C ha^{-1} year^{-1} (Forrest and Ovington 1970).

Observations in stands with Douglas fir and Norway spruce as well as in gradients. Using a chronosequence of Douglas fir stands, Turner and Long (1975) found a linear increase in the forest floor carbon (Fig. 11.3b, Table 11.1). In a comparison over a geographic range from Central Germany to North Italy, across the alpine region, Thuille and Schulze (2006) could relate the growth of the SOM layer carbon stock in Norway spruce forests to stand age in spite of the wide range

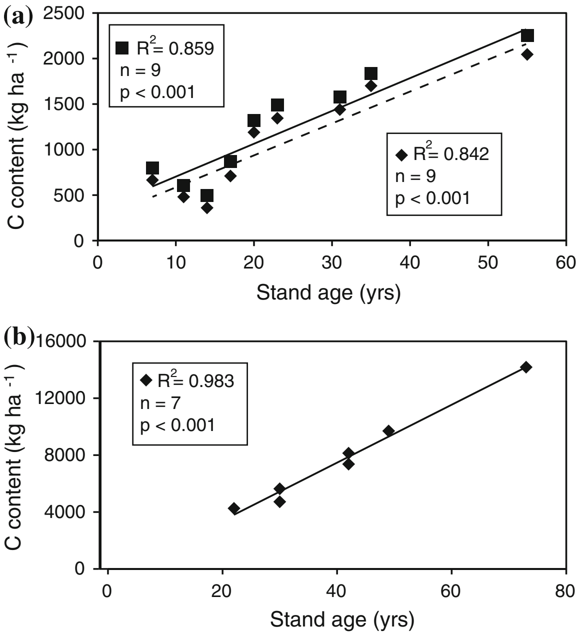


Fig. 11.3 **a** Accumulation of carbon in; (◆) the F + H layer of 9 Scots pine stands in a chronosequence with an age range from 7 to 55 years and (■) all dead organic matter in the forest floor. From Ovington (1959). **b** Accumulation of carbon in; (◆) the F + H layer of 9 Douglas fir stands in a chronosequence with an age range from 22 to 72 years. From Turner and Long (1975)

Table 11.1 A comparison of accumulation rates of SOM-C in forest floors in which the accumulation has been followed over time (stand age or in a chronosequence). The estimated increase rate in the measurement period is given as the slope of the linear function between accumulated amount and time

Species	Increase rate (Kg C ha^{-1} $year^{-1}$)	MAT	MAP	R^2	*p*<	Location Comment	Ref
Scots pine	380	9.5	517	0.859	0.001	England	(1)
Scots pine	537	9.8	827	0.627	0.001	Central Holland	(4)
Scots pine	196	5.8	615	**	0.05	South Germany	(8)
Scots pine	0	7.2	650	**	ns	South Germany	(8)
Monterey pine	1032	nd	1450	0.903	0.05	N So Wales Australia	(2)
Loblolly pine	237	12.8–15.6	1020	0.935	0.001	SE USA	(3)
Douglas fir	407	9.4	1440	0.982	0.001		(7)
Norway spruce	1106	5.3	1163	0.816	0.001	Central Germany	(5)
Norway spruce	360	7.7	600	0.887	0.01		(6)
Norway spruce	340*	5.8–6.8	815–1370	0.88	0.001*	Acid soils	(9)
Norway spruce	240*	4.1–7.5	661–1466	0.73	0.001*	Calcareous soil	(9)
Common oak	80	7.7	600	0.340	ns		(6)
Common beech	422	5.3	1163	0.609	0.05	Central Germany	(5)

* 6 chronosequences were investigated in the southern, central, and northern part of the Alps from Northern Italy to eastern Germany. P values estimated from data given in paper. ** Three samplings over 22 years. *ns* not significant. *nd* not determined

(1) Ovington (1959), (2) Forrest and Ovington (1970), (3) Schiffman and Johnson (1989), (4) estimated from Tietema (2004), (5) Berg (2004), Meesenburg et al. (1999), Maiwes et al. (2002), (6) Vesterdal, Ritter and Gundersen (2002). (7) Turner and Long (1975), (8) Prietzel et al. (2006). (9) Thuille and Schulze (2006)

in climate expressed as both MAT and MAP. This gradient had six sites with a range in MAT from 4.1 to 7.5 °C and MAP from 661 to 1466 mm. Further, each of the sites had a chronosequence with 4–6 stands plus an old control stand, in all 39 stands (both acid and calcareous soils). With the exception of the two oldest stands, the increase fitted a linear relationship very well (Fig. 11.4).

We may note that although an increase in SOM-C at a high rate appears normal, this kind of measurements is taken in well-documented forest stands that are managed. Management often includes a control on the number of stems per hectare and basal area. Such stands are thinned, which means that also litter fall is limited.

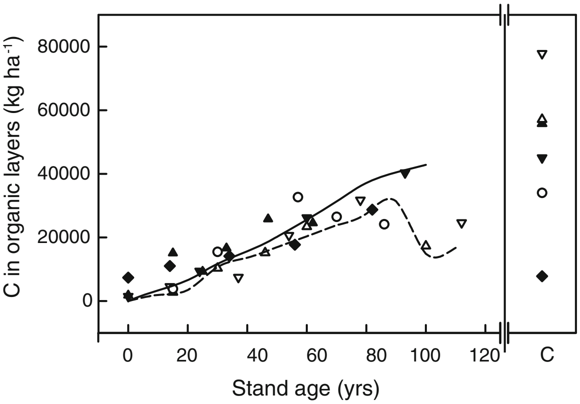


Fig. 11.4 Development of carbon stock in the organic layer of Norway spruce stands of different age in a gradient from east central Germany to north Italy. Black symbols show stands on acid bedrock, and open symbols show stands on calcareous bedrock. Redrawn from Thuille and Schulze (2006)

An exception is a stand of Norway spruce (Table 11.1) at Solling in Central Germany with an increase in the organic layer of 1106 kg C ha^{-1} year^{-1}. That stand was abnormally dense.

Some examples on deciduous forests. We have found two studies on deciduous species, namely on common oak (south Sweden) and common beech (Central Germany). The latter showed a significant linear increase in forest floor carbon with increasing stand age (Table 11.1).

11.4 Variation in Carbon Sequestration Rates among Tree Species and Soil Properties: Data for Northern Europe

11.4.1 Large-Scale Comparisons among Species Over Northern Europe

There is a limited number of studies useful for determining C sequestration rates in mor humus layers. Still, an inventory of existing data allows a certain synthesis as well as a few conclusions.

There is a clear variation in C sequestration rates in forest floors including both FH and LFH layers (Table 11.1), with the full range in measured values over the northern half of Europe, ranging from about 0 to 1,100 kg C ha^{-1} year^{-1}, the latter for a dense Norway spruce stand at Solling in Central Germany (Berg 2004).

In a first approach to analyze and distinguish a pattern, we combined two larger sets of data with in all 10 trials, one from England (Ovington 1954) encompassing three species trials and one from Denmark (Vesterdal and Raulund-Rasmussen 1998) encompassing 7 trials. The studies had very similar design and overlapping tree species. A brief overview to the main experiment; Vesterdal and Raulund-

Rasmussen (1998) used a tree trial experiment started 30 years earlier. That experiment investigated growth and humus formation of c. 16 tree species at 14 locations over Denmark. Each plot had a monoculture and measured at least 0.25 ha. All tree species on all locations were planted in the same year (Holmgaard and Bang 1977). One difference between sites was the type of soil and its richness in weatherable nutrients. Denmark is a rather flat land, and all sites were located within a circle with a radius of less than 150 km, which means that the climatic differences were minimal. The climate, expressed as MAT and MAP, ranged between 7.5 and 8.4 °C, and 610 and 890 mm, respectively. The mineral soil was bare at time for planting, meaning that the humus layer on top of the mineral soil had accumulated after the stands were planted. Further, all the organic material accumulated had formed a clearly distinguishable layer on top of the mineral soil. Thus, samples of the O horizon in a set of stands could be compared. Further, the similarities in the design of the experiment and in climate between stands allow data to be evaluated statistically as a block experiment. The experiment of Ovington (1959) had a very similar design with overlapping tree species and genera.

At all 10 sites, the forest floor was sampled once in stands of known age. SOM was sampled, and live plants plus branches were removed from the sampled material, which leaves foliar litter plus FH layer material for those stands in which a clear mor/moder humus layer was formed. In both studies, ash or C was determined and subtracted from the mor humus. We estimated the amount of carbon by assuming 50 % C in the organic matter of Ovington's study. Further, the amounts given by the authors were divided using stand age to give the annual C sequestration. Because of the similarities in climate, approach, and method as well as in tree species and genera in monocultures, we have combined data and compared values for the genera *Pinus, Picea, Pseudotsuga, Abies,* as well as *Quercus* and *Fagus.* In the evaluation, we used ANOVA.

The obtained dataset encompassed 75 values showing a large variation with a range in sequestration rates from 24 to 696 kg C ha^{-1} year^{-1} (Fig. 11.5). Within the group 'coniferous' ($n = 53$), the sequestration rates ranged from 63 to 696 kg C ha^{-1} year^{-1} and within 'deciduous' ($n = 22$), from 24 to 642 kg C ha^{-1} year^{-1}.

We may see that also at genus level, there is a large variation (Fig. 11.5, Table 11.2). Thus, the group pine spp encompassing 11 values for Scots pine, lodgepole pine, and Corsican pine had an average rate of 470 kg C ha^{-1} year^{-1} and a range from 125 to 696 kg C ha^{-1} year^{-1}. The largest group was that for spruce species with 17 values, encompassing Norway spruce, Sitka spruce, and Serbian spruce. The mean value was 364 kg C ha^{-1} year^{-1} and the range 151 to 693 kg C ha^{-1} year^{-1}. For *Pseudotsuga* and *Abies*, there was just one species in each group namely Douglas fir and Grand fir with averages of 266 and 189 kg C ha^{-1} year^{-1}, respectively, and ranges from 65 to 531 and 63 to 498 kg C ha^{-1} year^{-1}, respectively.

The averages for common beech and oak species were 277 and 90 kg C ha^{-1} year^{-1}, respectively, with ranges from 86 to 642 and 24 to 273 kg C ha^{-1} year^{-1}, respectively. We may see that the deciduous genera have clearly lower

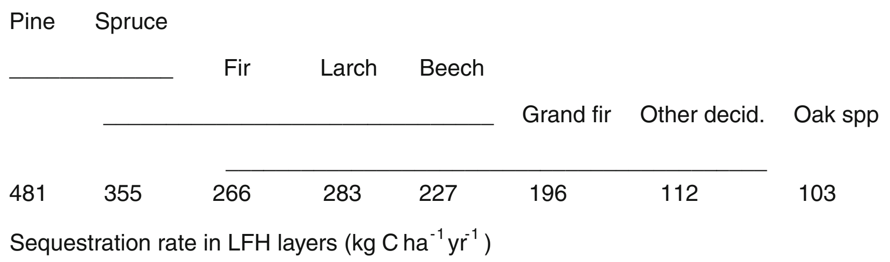


Fig. 11.5 Carbon sequestration data from 3 tree species trials in England (Ovington 1954) and 7 in Denmark (Vesterdal and Raulund-Rasmussen 1998). Each study gave a very carefully determined amount of soil organic matter on top of the mineral soil in monocultural stands. Data were combined to show the variation among genera. The full line underlining genera indicates accumulation rates that are not significantly different. Ash was subtracted, and we assumed 50 % C in the organic matter of Ovington's study (cf Table 11.3)

Table 11.2 Average sequestration rates for carbon bound in organic (L+F+H) layers in some monocultural planted forest stands. Measurements were made as one-time inventories of ash-free humus

Genus	Species	Average rate (kg C ha^{-1} $year^{-1}$)	S.D.	*n*
Coniferous genera				
Pinus	Lodgepole, Scots, Corsican	470	167.1	11
Picea	Norway, Sitka, Serbian	364	176.1	17
Pseudotsuga	Douglas fir	266	153.7	10
Abies	Grand fir	189	151.7	9
Larix, Thuja, Tsuga, Chamaecyparis		255	57.5	6
Deciduous genera				
Fagus	Common beech	227	203.9	8
Quercus	Common, red, sessile	90	77.6	11
Alnus, Betula, Castanea	Gray alder, white birch, chestnut	90	27.3	3
Main groups				
All coniferous		326	183.6	53
All deciduous		140	150.2	22

We have combined available data for some main genera from forest stands in Denmark and England (Vesterdal and Raulund-Rasmussen 1998; Ovington 1954) and estimated average rates from time for planting. All Danish stands were 30 years of age, and the age of the English ones ranged from 17 to 46. See also Fig. 11.5

S.D. Standard deviation

sequestration rates than the coniferous ones. In fact, the value for the group 'deciduous' is significantly lower than that for 'coniferous' ($p < 0.0001$; *t*-test; Table 11.3).

It is evident that in such a comparison, both the litter production, which is related to growth rate of trees (determining litter fall), and the stable fraction (100-limit value; Chap. 10) are variable. In these and similar comparisons, such factors

Table 11.3 Significant differences (p values) in SOM-C sequestration rates. Differences in LFH layers between different genera, as well as the main groups coniferous and deciduous. cf Fig. 11.5

	Spruce spp.	Douglas fir	Grand fir	Common beech	All decid.
Pine spp	0.068	0.006	0.0003	0.007	
Spruce	–	0.086	0.012		
All conif.					<0.0001

The average values from Table 11.2 were compared using t-test

as stand density and management are assumed to be similar enough to allow a combination of data.

A further study may support this result. Berg (2004) using data from Maiwes et al. (2001) and Meesenburg et al. (1999) compared the increase in forest floor C with time and estimated rates of 1100 and 320 kg C ha^{-1} $year^{-1}$ for Norway spruce and common beech, respectively. The stands (Central Germany) were paired, confirming a difference between species on the same soil. In that case, the Norway spruce stand was extremely dense, which may explain the very high rate.

11.4.2 Accumulation of SOM-C with Climate: Coniferous Forests in Gradients

There are gravimetric studies on C sequestration rates in SOM of coniferous forests, both in single stands and in chronosequences of mainly Scots pine, lodgepole pine, Norway spruce, and Sitka spruce. The rates vary considerably, and values between 0 and 1,100 kg C ha^{-1} $year^{-1}$ have been measured within the group ‘coniferous.’ Although there are few studies, they allow some conclusions that may be of guidance for further work.

The data originate from northern to south Sweden, Denmark, central Netherlands, central Italy, the UK, east Canada, and south Italy. In all cases, we compared SOM-C in an organic layer. Wood on the forest floor was excluded. In this relationship, we used information for the main coniferous genera, viz. spruce, mainly Norway spruce and pine spp. For the extensive experiments of Vesterdal and Raulund-Rasmussen (1998), we used average values for the two temperature (MAT) regimes given by them.

We found increasing sequestration rates with increasing MAT (Fig. 11.6). Although pine spp. has an almost significantly higher sequestration rate than spruce within a climatically homogeneous area ($p = 0.068$; Table 11.3; Sect. 11.4.1), we found that over this gradient, there was a clearly significant ($p < 0.01$) relationship between C sequestration rate and MAT when combining coniferous species.

A further example is presented and discussed in Sect. 12.5.6. Using a long-term (41 year) forest floor inventory covering the forested land of Sweden, Berg et al. (2009) found a highly significant positive relationship between temperature sum

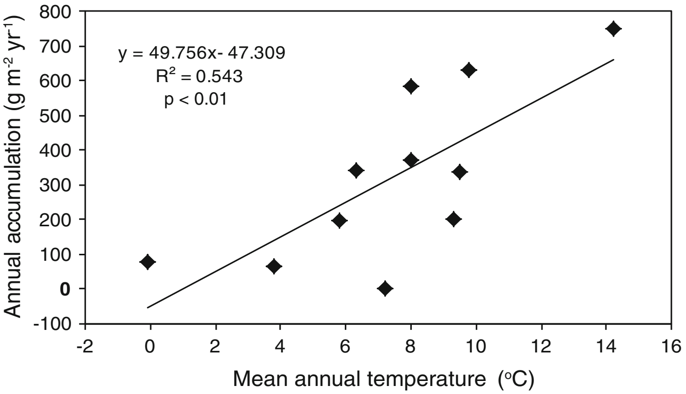


Fig. 11.6 Carbon sequestration rates in humus layers (kg C ha^{-1} $year^{-1}$ in coniferous forest stands ranging from north Scandinavia to south Italy, MAT range c. 0.1 to 11 °C. Available data originated both from chronosequences and from stands with controlled growth of an organic layer (one sampling). Scots pine, lodgepole pine, black pine, Monterey pine, Norway spruce, Sitka spruce, and Douglas fir. Available data for single stands and chronosequences from Tietema (2004), Berg and Staaf (1977), De Marco et al. (2012), Wardle et al. (1998), Vesterdal and Raulund-Rasmussen (1998), Ovington (1959), Turner and Long (1975), Sogn et al. (1999)

and carbon sequestration rate (measured humus accumulation). Temperature sum is defined as the sum of daily mean temperature exceeding +5 °C and calculated from latitude and altitude (www-markinfo.slu.se; Odin et al. 1983). They divided the country into 25 × 25 km grid cells and related humus depth to temperature sum. Using all plots with both Scots pine and Norway spruce, they found a positive linear relationship with the temperature sum ($R^2 = 0.29$, $n = 548$, $p < 0.0001$).

As discussed above, the SOM-C sequestration rate may be estimated from litter fall and the size of the stable litter fraction. Litter fall may be related to MAT, and at least for pine spp the stable fraction has been related indirectly to MAT. Although a relationship like that in Fig. 11.6 is empirical and needs further resolution, we may expect that at least short-term accumulation may have a causal relationship with MAT.

11.5 Some Factors Related to Mineral Soil may Influence Organic Layer C Sequestration

Soil factors include both physical and chemical properties. Texture is perhaps the most important physical property of soil because it influences nutrient and water dynamics, porosity and permeability, as well as surface area. Chemical properties include pH, cation exchange capacity, and organic matter content, all of which can influence the mobility of nutrients and the composition of the microbial community.

11.5.1 Soil Texture and Mineral Soil Nutrients

An experiment that may give a new view on the effect of nutrients and/or mineral soil structure on the long-term decomposition process as well as on storage or sequestration of organic matter on top of the mineral soil was that made by Vesterdal and Raulund-Rasmussen (1998) (cf above).

With 10 replicates per stand, Vesterdal and Raulund-Rasmussen (1998) measured the amount of LFH layer (and carbon) accumulated at 7 sites. Using 7 tree species, namely lodgepole pine, Norway spruce, Sitka spruce, Douglas fir, Grand fir, common oak, and common beech, they found clear differences among sites both as regards the chemical composition of the remaining organic material (humus) and as regards the amounts of sequestered carbon on top of the mineral soil.

They found an effect related to site (Fig. 11.7b). Taking the average values of all tree species for each site, they obtained average amounts that were significantly different. Carbon content in the O horizon was negatively correlated with mineral soil pH and to soil clay content; the coarser the soil structure is, the more was stored. Thus, carbon content in the humus layer was related to properties of the underlying mineral soil. The amount decreased with increasing concentrations of clay and silt and increased with increasing concentrations of coarse sand.

They related concentrations of extractable (plant available) mineral nutrients, originating from the mineral soil to the amounts of carbon sequestered. Amounts of carbon on top of the mineral soil decreased with increasing concentrations of extractable P, Ca, K, and Mg. They concluded that soil texture, Ca, and P concentrations appeared to be the most important variables for the amounts of C in the forest floor. When comparing concentrations of P with forest floor mass, clearly negative relationships were seen between the amount of carbon sequestered in the O horizon and mineral soil concentration of extractable P (Fig. 11.8).

Lodgepole pine forests stored the highest amounts and significantly more than the two spruce species and seemed not to be influenced by available Ca or P in the mineral soil. Although the stored amounts were generally lower at higher concentrations of Ca and P (Fig. 11.8), there was a tendency to order among species mainly like in Fig. 11.7. Lodgepole pine allowed significantly more carbon to be stored than common beech, which in its turn stored more carbon than common oak. Douglas fir and Grand fir were in between.

11.5.2 Organic Layers' Natural Nutrient Availability

Of the single species, lodgepole pine had formed an O horizon that was beyond comparison more nutrient poor than those of the other species. In general, Grand fir, common oak, and common beech had the most nutrient-rich organic layers (Table 11.4). Worth noticing is that lodgepole pine had the most C accumulated in the forest floor and the three latter species, the least.

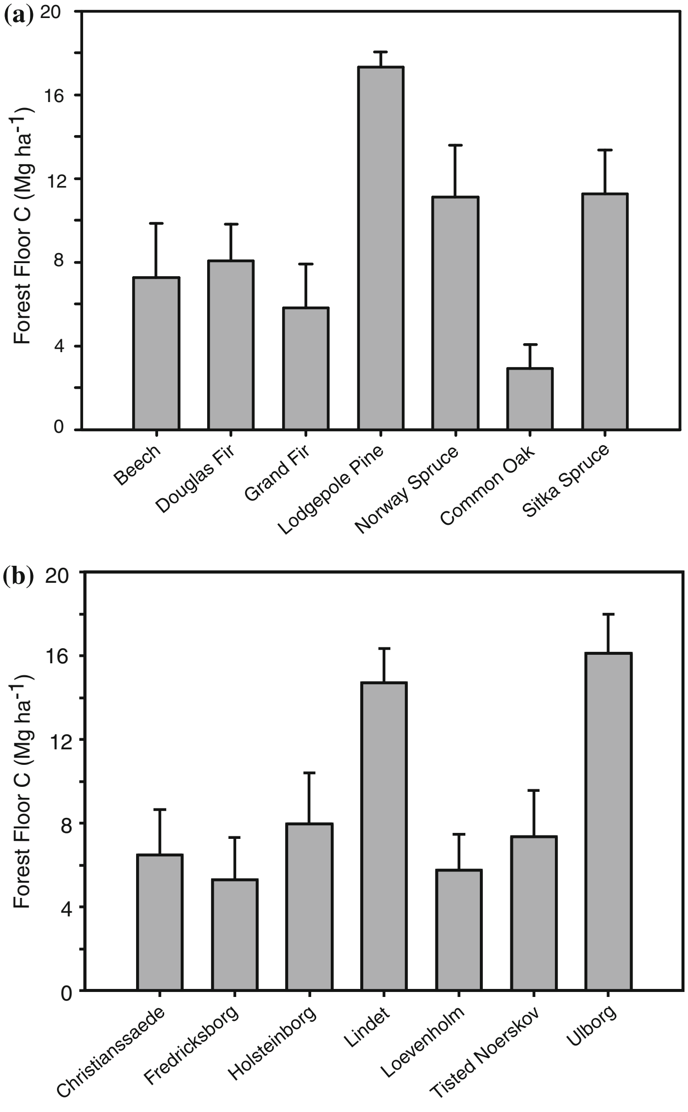


Fig. 11.7 The average amount of carbon in humus layers formed in stands of seven monocultures of different tree species. The same tree species were planted at seven different sites with soils of different richness. The figure gives average amount of carbon stored in humus. **a** Average values for tree species over the seven sites. **b** Average values for all tree species within each site. The figure thus suggests an effect of both tree species and site. Bars with the same letter indicate no significant difference at $p < 0.05$. Abbreviations: O. common oak, B. common beech, DF. Douglas fir, SS. Sitka spruce, NS. Norway spruce, LP. lodgepole pine. From Vesterdal and Raulund-Rasmussen (1998)

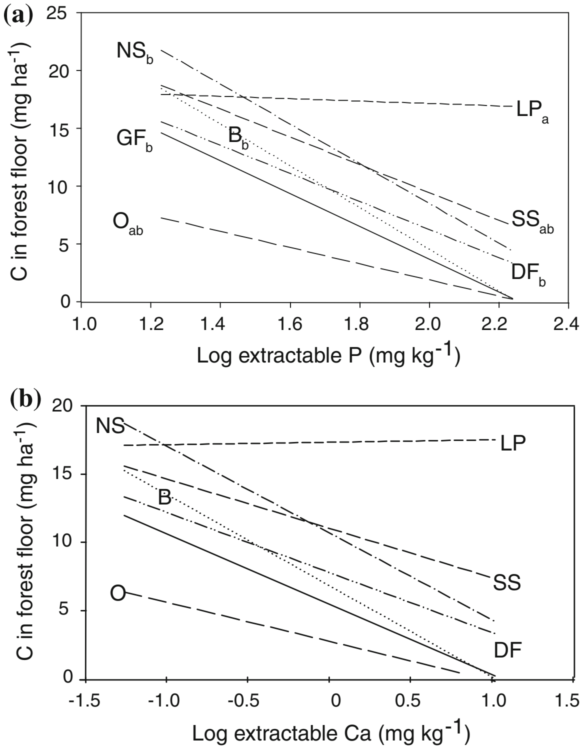


Fig. 11.8 **a** Linear relationships between average concentrations of extractable P in the mineral soil (0–50 cm) and amounts of carbon in the forest floor for seven tree species. Lines with the same lowercase letters do not have significantly different slopes ($p < 0.05$). **b** Linear relationships between average concentrations of extractable Ca in the mineral soil (0–50 cm) and amounts of carbon in the forest floor for seven tree species. From Vesterdal and Raulund-Rasmussen (1998)

Table 11.4 Average values for soil nutrients as related to the organic fraction of the forest floor, formed under seven tree species in a tree trial experiment on different soils and very similar climate

Tree species	C/N	C/P	C/Ca	C/K	C/Mg
Lodgepole pine	35.2	674	264	805	753
Sitka spruce	28.7	530	94	533	648
Norway spruce	26.4	462	77	412	480
Douglas fir	31.4	434	114	462	546
Grand fir	26.8	465	58	438	482
Common beech	26.8	465	48	337	396
Common oak	27.5	440	55	315	398

From Vesterdal and Raulund-Rasmussen (1998)

Although nitrogen is a nutrient that often is limiting, it is one that originates from the air, like carbon. Like carbon, it is taken up by fixation processes through plants, except for the N deposited in the natural background deposition. Still, an index for a soil's ability to store carbon would also be an index for its ability to store nitrogen as these two compounds are sequestered and stored together, let be in different proportions as dependent on species (Table 11.4).

The finding of Vesterdal and Raulund-Rasmussen (1998) relates to a period that may correspond to a certain stand age (30 years). Assuming that soil properties affect the soil microorganisms, such effects may decrease as a humus layer develops and the immediate environment for the microorganisms change. Although this may take some time, it may mean that we cannot exclude the possibility to find well-developed humus layers under deciduous stands also on rich soils.

11.6 Humus Layer Stability versus its Turnover

A relative stability or a slow decomposition is, in general terms, a condition for the accumulation of humus. We discussed (Sect. 10.2) the relative stability of the organic matter at the limit value.

Berg and McClaugherty (2003, 2008) discussed four main classes of humus turnover or disturbed stability. First, there is humus decomposition in completely undisturbed humus. Further, there is decomposition associated with elevated microbial activity, one being caused by a strongly activated mycorrhizae, a third due to mechanical disturbances caused by soil manipulation and drainage leading to radically higher decomposition rates. Finally, high rates of humus turnover have been observed in humus subjected to very high N inflows.

We have not found any studies of humus decomposition or stability relating to causal factors in really undisturbed soil systems. However, Berg and Matzner (1997) reported a study on respiration rates from humus cores, incubated in the laboratory under standard temperature and moisture conditions. Humus samples with differing N concentrations showed very different respiration rates that were negatively related to concentration of N in humus (Fig. 10.3). If we consider the respiration rate as measure on stability/instability of the humus fraction, we may conclude that the stability increases with increasing N levels; still, our conclusion is limited to the set of measured data.

11.7 Carbon in the Mineral Soil

The amounts of carbon in mineral soil in the boreal forest are estimated to be up to 60 times that in the organic layers although there is a high variation among sites. Further, it is considerably more stable to degradation (DeLuca and Boisvenue 2012).

11.7.1 Does the Amount of Organic Matter in the Mineral Soil Change?

The storage or sequestration of carbon in the mineral soil appears to follow another pathway than that in an organic layer. Berg et al. (2008) suggested the term 'secondary sequestration' (Fig. 11.1). Later, De Marco et al. (2012) presented an example of two forest stands, one with black pine and the other with black locust where the former mainly formed a clear humus layer on top of the mineral soil and the black locust stand appeared to have a higher fraction stored in the mineral soil. The sequestration patterns thus were different, supporting different pathways. This may illustrate that one species/genus may cause sequestration in an organic layer and another may produce organic matter that is less stored on top of the mineral soil, but possibly, in part degraded and solubilized components are precipitated in the mineral soil.

Investigations have been made as regards changes in the C amounts in mineral soil with time, and even long-term investigations give about no measurable change. In a temperate mixed deciduous forest (MAT c. 12 °C), Kiser and Johnson (2009) did not see any large-scale change in amount over a period of c. 30 years. Working in a watershed in Tennessee (USA), they had identified 8 soil types, and when taking an average, no increase was found. However, subdividing their data according to soil type gave new information. They found significant changes in carbon concentration and amount in the top 10 cm of the mineral soil. Their data show that even within a limited area of 94 hectares, there may appear significant both increases and decreases.

Another study (Johnson et al. 2007) from a watershed in the same region gave variable results. Over 30 years, there was an increase in the upper 0–15 cm of the mineral soil in most cases and a high variability.

11.7.2 Organic Matter Mixed into the Mineral Soil

One of the first long-term studies to examine the effects of soil properties on decomposition was that by Jenkinson (1977). He examined the decomposition of ^{14}C-labeled ryegrass in a variety of soils. In these soils, clay content ranged from 5 to 21 %, pH from 3.7 to 8.1 and organic C from 0.97 to 4.57 %. He found that neither organic matter content nor pH had much impact, except that decay was initially slower in the most acidic (pH 3.7) soil. On the other hand, soil texture was an important factor, with more litter-derived C retained in soils with higher clay content. Similarly, the total soil organic matter levels were less in sandy soils (14 %) than in soils with more clay (up to 29 %). This suggests that mineral soils with clay are able to hold onto more biologically degradable SOM than are sandier soils. Several mechanisms could account for the influence of soil texture on decomposition.

Because soil texture is so closely related to soil water dynamics, Scott et al. (1996) undertook a study to examine the effects of both soil texture and soil water pressure. They made artificial soils by blending soils collected from the field. Their soils had sand contents of 40, 55, and 73 %. In each of these soils, they regulated water at −0.012, −0.033, and −0.30 MPa. This combination of treatments yielded a continuum of water content that they described with a single variable, percentage water-filled pore space. Soil texture had no effect on the decomposition of wheat litter. However, there was an interaction between soil texture and water pressure, such that the effect of water pressure was negligible in the sandy soil and was greatest in the loam soils. Also, noteworthy was that the effects of soil texture and water pressure on litter decomposition were very much less than their effects on the decomposition of the older C that was already in the soil.

We conclude that soil texture is more important for long-term organic matter dynamics than for initial phases of decay. Not surprisingly, finer-textured soils will interact with water more than coarser-textured ones. As a result, water levels generally influence decay relatively little on sandy soils, but have a significant effect on loams or finer-textured soils.

11.7.3 Is There any Effect of Disturbance?

There appears to be different dynamics of humus (carbon) in different soil layers, and to illustrate this, we have selected a study carried out in stands of Norway spruce and common oak (Vesterdal et al. 2002). Using the same stands, the authors followed the concentration of carbon in the organic layer and in three layers of mineral soil, namely at 0–5, 5–15 and 15–25 cm. In the studied case, the concentration of newly stabilized carbon increased in the organic layer (Fig. 11.9) over a period of 29 years and in the top mineral soil (Fig. 11.10). However, in the two lower layers (5–15 and 15–25 cm), a decrease was statistically significant and in the magnitude of 250–290 kg carbon per hectare and year, respectively, for each of these two lower layers. The mineral soil had been plowed before the stands were planted and that the concentration of carbon in the mineral soil is decreasing is very likely a consequence of that. That a disturbance of soil activates the soil microorganisms is well known to soil microbiologists, and Fig. 11.10 gives a

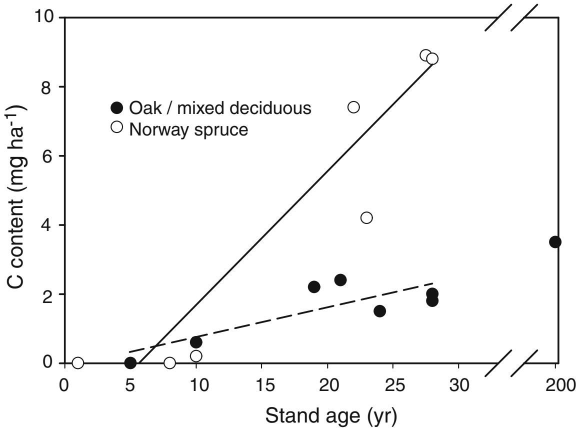
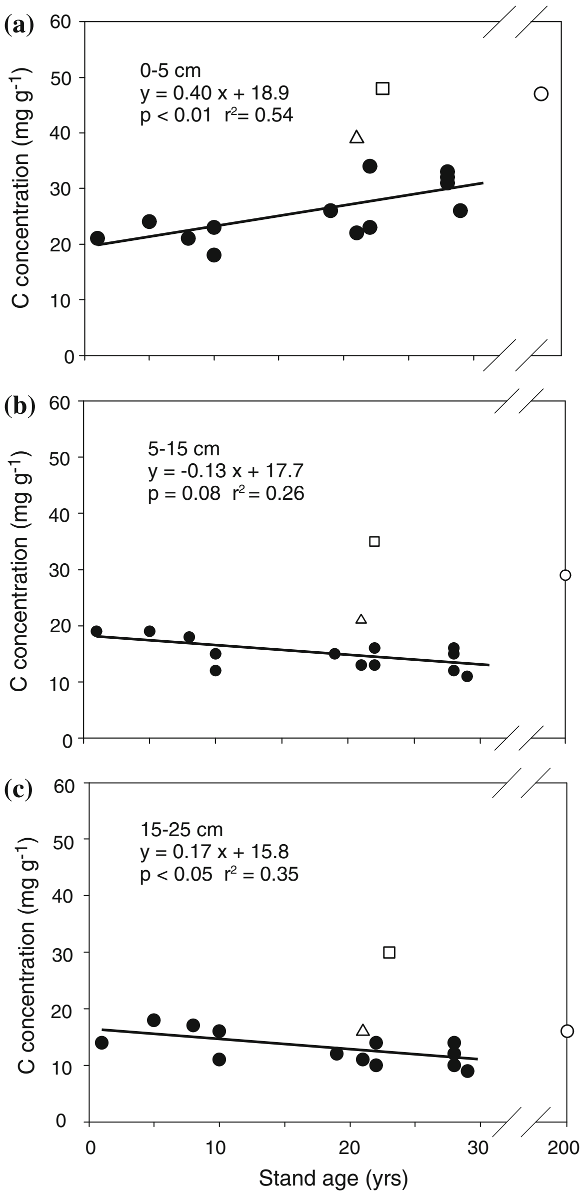


Fig. 11.9 Absolute amount of soil carbon in the organic layers in chronosequences of Norway spruce (○) and common oak (●) up to 29 years of age. All studies were carried out on the same soil and under the same climate. Redrawn from Vesterdal et al. (2002)

Fig. 11.10 Carbon concentration in three mineral soil layers in a chronosequence of Norway spruce (●) and an adjacent c. 200-year-old mixed deciduous plantation (○). One adjacent Norway spruce stand (□) was excluded from the regression. Permanent pasture (△)



quantification of this effect, resulting in a clear decrease in carbon concentration over at least 28 years since the disturbance. We have selected this study to illustrate this kind of effect, which also is likely after, for example, ditching or site preparation of a forest soil, allowing air (oxygen) to penetrate deeper soil layers.

We do not know the limitations of this effect, and the question remains whether a similar decrease in carbon in deeper soil layers is found after such disturbances as a clear-cut or after a forest fire. A consequence may be that there is a new formation of stable matter, whereas for old organic matter that has been disturbed, a degradation may take place.