Chapter 12
Estimating Carbon Sequestration Rates on a Regional Scale

12.1 Long-Term Accumulation of Carbon in Organic Layers (O Horizon): General Comments

In Chaps. 10 and 11, we discussed the fraction of litter that we considered stable and the buildup of a humus layer. Further, we discussed the accumulation of humus and its stability in single plots and in single stands. In our examples, we used the stable fraction (100-limit value) for one litter type, namely foliar litter, to calculate the amount of humus in a given stand. It is evident that humus layers are built up from different litter components, not only the foliar litter from the trees, although this litter component is a dominant one. Ideally, we should have used limit values for a whole set of litter components, at least the major ones and added stable fractions for litter components such as leaf litters from the ground vegetation, from moss, from other tree litter components such as cones and woody material, for example twigs. We can make the list longer. For a proper quantification, this is evident. Unfortunately, the available information to do this is lacking. The only litter component for which there exists reasonable information is the foliar one from trees, both as regards litter production and as regards the decomposition process. We have discussed the possible formation of stable humus from other litter components, and we cannot exclude that, for example, woody litter may produce just a small fraction. Litter production from, for example, moss is not really quantified and decomposition experiments lacking. Litter production from roots is also too little known, and decomposition experiments have so far not given unequivocal results in undisturbed systems.

The fact that we could reconstruct quantitative accumulation of mor humus for a period of close to 3,000 years (Sect. 11.2) using limit values and remaining stable fractions for foliar litter does not exclude the possibility that, at least in boreal coniferous systems, the foliar litter component is a major one as regards formation of humus in an organic layer.

B. Berg and C. McClaugherty, *Plant Litter*, DOI: 10.1007/978-3-642-38821-7_12,

Most decomposition studies are made on a short-term basis and give information with a short-term perspective, namely a few years. Sequestration of carbon is a process that is a result of the decomposition process, but should be observed and ideally studied over periods of centuries, millennia, or at least decades. In Chap. 11, we followed the C sequestration for smaller areas such as stands and short gradients, studied with a corresponding methodology, namely direct sampling and gravimetric determination. In this chapter, we have taken a further step and estimate the buildup of humus over a region. Further, we compare the results of an upscaling to a region to those of single stands. The specific region we use for the case study is the forested area of Sweden, and the stands for comparison are located over Scandinavia and Northern Europe.

When organic matter accumulates in boreal and temperate forest soils, two main fractions can be distinguished, functionally and spatially distinct and different. One fraction forms a more or less distinct organic layer, and the other is found in the mineral soil. These main fractions are best separated in mor humus and considerably less in mull. Focusing on our regional case study, the organic layer on top of the mineral soil (O horizon) is mainly a mor humus layer, which has facilitated or made the quantification of amounts over time possible.

The organic layer fraction may be built up rather quickly but is vulnerable to forest fires. With a natural fire frequency, sometimes as high as one every 50–60 years, organic layers at drier sites rarely have reached a mass of any magnitude. However, today's efficient prevention of wild fires has resulted in a significant general increase in the mass of the O horizon, and in smaller, isolated plots that have not been reached by fire, an accumulation over millennia may be found (cf. Wardle et al. 1997).

There appears to be very different mechanisms for the sequestration in an organic layer and in the mineral soil. These two main layers have different properties and different protection, and we may need to specify what we refer to. The organic layer on top of the mineral soil (e.g., a mor layer) is where the 'primary' sequestration takes place (Glossary, Appendix I), namely the accumulation of the stable fraction of litter. The carbon sequestered in the mineral soil is transported either in soluble form or as aggregates and precipitated in the mineral soil. Further, decomposing root litter gives an addition. It appears natural to call this a secondary sequestration (Berg et al. 2008). We have defined these concepts (Glossary, see also Fig. 11.1).

An often-expressed a priori assumption in ecosystem studies is that the system either is in or approaching a 'steady state,' a notion that has been effectively challenged by Botkin (1990). This is especially true as regards the amount of carbon or other materials found in the system, and this assumption deserves to be questioned. We have already discussed this (Sect. 11.2), and in this chapter, we develop the discussion to a region.

12.2 Influences on Carbon Sequestration Rates in Forested Land: Regional Level

12.2.1 Undisturbed Sites and Anthropogenic Influence

Some factors influencing the C sequestration rates over a region are evident, such as variation in climate, soil nutrients promoting tree growth, tree species, forest management, and N deposition, and we will discuss them briefly.

We discussed the concept of stable residue earlier (e.g., Sects. 2.6.3, 6.4) and that litter chemical composition influences the size of the stable fraction as defined by the limit value. When applied to single stands on relatively nutrient-poor soil, it has been possible to relate foliar litter fall and stable residue to humus accumulation rates with acceptable precision (Sect. 10.4.1). However, over a region, the number of factors that may influence the sequestration rate increases, variation in climate being a prominent one with warmer and wetter climates, giving, for example, a higher production of litter. Further on, climate also has an effect on litter chemical composition (Chap. 4). Also, tree species may vary with climate and with soil type, resulting in litter inputs of different magnitudes and of different chemical compositions.

Climate. Over a region, climate influences tree growth rate and litter fall (Liu et al. 2004; Berg and Meentemeyer 2002) and litter chemical composition both within species (Figs. 4.1, 4.3, 4.6) (Berg et al. 1995) and over species (Liu et al. 2006), normally resulting in higher concentrations of at least N with increasing MAT or AET. Decreasing concentrations of Mn have been observed with increasing AET and MAT (Berg et al. 1995, 2010). Further, AUR concentration appears to be positively related to that of N at least for some litter species (Fig. 4.2) (Berg et al. 2013).

Tree species. Different species produce foliar litter at different rates and have different substrate qualities, that is, different concentrations of Mn and N, which should affect limit values and the sequestered amounts of C (Sect. 10.3.2; Fig. 10.2) and could be expected as a significant factor over larger areas.

Soil nutrients and substrate quality. Over a region, the availability of nutrients may vary, both as regards N and as regards weathered nutrients. The bedrock may form a patchwork of properties as regards the mineral soil, which influences the availability of different nutrients through their concentrations and by pH. A soil richer in nutrients can promote a higher tree growth rate and thus a higher litter fall. Natural soil properties may vary violently even within small areas and create very different intensities in litter fall. Also, substrate quality will be influenced. We have discussed and focused on the effects of mainly N and Mn on the limit value and the stable fraction.

Anthropogenic factors. As regards forest management practices, they may vary and be different over a larger region. Ditching, site preparation, fertilization, clear-cutting, and other harvest policies can influence SOM accumulation. As far as we can tell, most forest management will clearly disturb the sequestration of soil carbon for evident reasons.

Site preparation may be done in different ways, and in some cases, the mineral soil is actually plowed just before planting the trees. The purpose is to activate the soil microorganisms and support a decomposition of organic matter and thus improves the nutrient supply. Such activation may have a long-lasting effect. In one study, an inventory of amounts of soil carbon in three soil layers was made in a chronosequence up to 29 years after site preparation. In the layer 0–5 cm, both the concentrations and amount of carbon increased, whereas in the layers 5–15 and 15–25 cm, both concentrations and amount decreased in the whole period. The top layer received a new inflow of carbon from decomposing litter, whereas the deeper layers did not (Fig. 11.10) (Vesterdal et al. 2002).

Clear felling means not only an interruption of the litter input but an additional disturbance of the upper soil layers including the absent root uptake of nutrients. Part of the decomposition process, namely that of newly shed litter, is removed, which results in an increase in soil pH and no addition of stable litter residue. Further, concentrations of available soil nutrients increase as well as the level of soil water. The absence of a growing forest and its influence on the soil, for example through the absence of root exudates, may change the properties of the remaining humus and influence its stability.

Nitrogen deposition/pollution may have a large-scale fertilization effect, possibly resulting in increased tree growth and litter production and an ensuing effect on SOM accumulation.

Afforestation and reforestation may mean an introduction of forest on land that has been agricultural; thus, on soil that may have been plowed, fertilized, and had crops over so long a time, the soil microflora may have been completely exchanged. It is possible that the soil simply has developed entirely new properties that may enhance or prevent decomposition of forest litter.

Although these factors are likely to be important, we have limited possibilities to discuss and quantify their effects here and will focus on the effects in natural and mainly undisturbed or less disturbed forests.

12.2.2 General Consideration as Regards a Database for Regional Modeling

For the upscaling of data to a region, we need forest information that is related to specific and identifiable geographical points and the information mentioned above may be part of such a database. The information should be organized into grid cells of a useful size such as those normally found in, for example, a national grid net. The grid cells could have different size depending on circumstances, for example 1 or 100 km^2. The total information associated with each cell can vary, but examples on information useful to our purpose would be tree species, stand age, some measure of stand density, the fraction of each cell covered by forest, and possibly soil data. It may be necessary to add information, for example estimated litter fall or climate factors.

Our case studies to estimate humus buildup and carbon sequestration will be different in character, and the databases thus will be different. Because much of the data utilized for each case study is unique, the databases will be discussed separately.

12.3 Two Case Studies

We present two very different case studies for the same region. The first one demonstrates carbon sequestration using data on *actual increases in humus depth as measured over* 41 years (Sect. 12.4). In the later section, we use the concept of *stable residue* (*limit values*) in decomposing litter and discuss an approach that can explain a potential buildup (Sect. 12.6).

Direct measurements of humus depth. In this case study, we present a method to evaluate direct measurements of humus depth over time, an approach that includes the effects of forest management and disturbance. The average measured accumulation rate is thus a net rate including the site-specific effects of wild fires, climate change, and forest management, such as site preparation.

Humus depth was thus measured at a high number of plots (tracts) over time, transformed to an area using Kriging for grid-net units and related to time for each such unit. In a last step, a transformation to amount of carbon was undertaken.

Stable residue. The discussion about a stable residue (limit-value) approach includes quantitative litter fall and litter quality as factors that influence the buildup of the O horizon. Effects of wild fires, forest management or other disturbances, and possible effects of mineral soil properties are not included. The calculations are based on foliar litter fall in mature stands and do not include the clear-cut phase. We may consider this a theoretical approach based on the assumption that all sequestration takes place in an organic layer (primary sequestration; Fig. 11.1).

As our estimates are based only on foliar litter, they would be expected to underestimate accumulation. In all cases, the estimated accumulation should be considered as order-of-magnitude estimates and serve to illustrate the potential for carbon sequestration in a particular forest as contrasted with the actual accumulation. However, we will offer some validation data to support the reasonableness of the estimates. We call this accumulation 'potential,' because the calculations cannot at this level include all possible effects of forest management and other disturbances and thus rather would give the potential accumulation.

12.4 Case Study for a Region: Direct Measurements of Humus Depth

12.4.1 Background

The amount of humus in, for example, a mor layer or in an O horizon may vary considerably also within a relatively small area, often making it difficult or even impossible to determine the amount with any accuracy or to follow a change in amount over time. Well-defined profiles as found in mor humus developed on sediment soil may give a relatively good basis for such determinations, whereas humus developed on till soil or perhaps on a slope will create a more difficult situation or even an impossible one.

With a high enough number of measurements over a long time, this kind of problem may be overcome, at least to some degree. In contrast to small-scale measurements (Chap. 11), the methods to cover a larger area may be different, and for example, a high number of repeated humus depth measurements may make it possible to cover a whole region.

In 1961, long-term measurements started in Swedish forested land: simple registrations of humus depth that were combined with chemical analyses of humus samples and determination of bulk density. In 2002, more than 800,000 single measurements had been made rather evenly distributed over a 41-year period and an evaluation was initiated. These values will serve as the foundation for our case study.

In this region, covered by the case study, there were just two tree species that dominated, namely Scots pine and Norway spruce, often in monocultures. In the database, the dominant species as determined by basal area was given for each of the measurement spots. Berg et al. (2009) also included a third type of forest called 'all species,' which includes all possible combinations of species, including, for example birch spp. This type also provided the rate that is representative as an average for the whole country. When presenting general representative data, the numbers for this 'all species' alternative are used.

12.4.2 General Design of the Humus Inventory

Annual direct measurements of humus depth were taken over a period of 41 years. The absolutely most common type of humus layer is the mor, and a clear O horizon was distinguished in all the cases used. Below, we discuss humus accumulation and carbon sequestration taking place in the humus layer on top of the mineral soil (primary sequestration).

In a first evaluation of humus accumulation rates, Berg et al. (2009) limited the analysis to podzols. A total of more than 800,000 single determinations of depth were made, resulting in a total of 127,139 average values for humus depth, each value being an average of at least five simple measurements. Of these, Berg et al. (2009) used 82,513 values for podzols.

The measurements of humus layers in this approach were taken in four separate inventories in the periods 1961–1972, 1973–1975, 1983–1987, and 1993–2002 (data on http://www-markinfo.slu.se). The sample plots were chosen randomly within a predetermined sampling pattern, and each year, 10–20% of the plots were sampled. Humus depth was measured, and at the same spot, a sample of the O horizon was taken and used for carbon analysis and bulk density determinations.

The measurements were taken in forests that were, and still are, subject to forest management practices such as site preparation, which has been ongoing since the 1960s. Newly planted stands were included, encompassing afforestation of agricultural land. No data were collected on mires, and the humus on practically all plots can be classed as mor.

12.4.3 Scaling up from Field Measurements on Humus Depth in Plots to C Sequestered on Country Level: Overview

The 82,513 measurement values distributed over the country were converted to values for grid cells in the national grid net by using Kriging interpolation. Thus, the measured depths were converted to average values for amounts of sequestered carbon in grid cells with a dimension of 25 × 25 km (Fig. 12.1). The calculation for each grid cell can be described in three steps. First, the increase in humus depth was determined over the 41-year period (e.g., Fig. 12.2). Second, the bulk density of humus given as amount of carbon per mm and hectare was calculated over time. In a third step, using bulk density and carbon sequestration, the increase in amount of carbon was calculated and given as kg per hectare and year. This sequence is given in Fig. 12.4a, b, c.

Humus-layer thickness. The thickness of the humus layer in each 25 × 25 km grid cell was calculated for each year as a weighted average using humus depth from all sampling plots located within a circle with a radius of 55 km (Fig. 12.1). The rates for increase in humus thickness (humus accumulation rates; given as mm per year) were then calculated for each of the 25 × 25 km grid cells by using a linear relationship between time and the thickness of the humus layer (Fig. 12.2). For the whole country, Berg et al. (2009) obtained 460, 505 and 548 such linear relationships for stands dominated by (1) Norway spruce, (2) Scots pine, and (3)

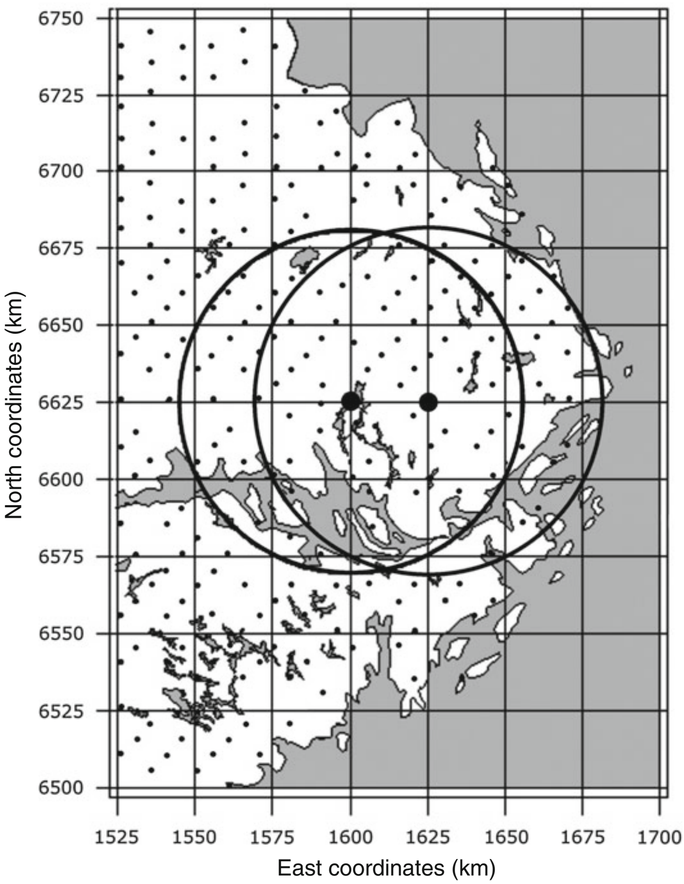

Fig. 12.1 Illustration of the use of the national Swedish coordinate system with intersection set at a distance of 25 km. Each intersection is the center of a circle with a radius of 55 km (marked with full line). All sampling plots located within such a given circular area were used for calculating the humus depth at the intersection, viz. the center of the circle. This spot was considered to be the center of a new quadrat (25 × 25 km) and represents the humus depth for that one. The calculated thickness of the humus layer in each intersection is a weighted mean using humus depth from all sampling plots located within the circle. Gray areas represent lakes and the Baltic. The black spots at uniform distances indicate sampling plots clustered together in tracts. From Berg et al. (2009)

stands without species dominance, 'all species' (Table 12.1). In this approach, only three groups were used, the third group, 'all species,' reflecting an average value over all species combinations.

Humus depth converted to carbon. Using bulk density for humus in each sampling plot (tract) as well as C analysis, they converted the annual increase in humus depth to increase in sequestered carbon. This was done separately for each of the grid cells.

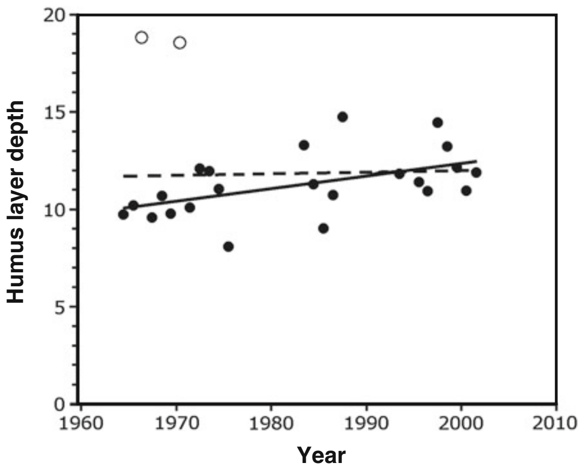

Fig. 12.2 An example of linear relationship at an intersection (cf Fig. 12.1) with humus-layer thickness related to time for both retained observations (*solid line*) and all observations, including those with too extreme studentized deleted residuals (*open circles, dashed line*). From Berg et al. (2009)

12.4.4 Changes in Organic Layer Thickness over Time

12.4.4.1 Overview to the Whole Case Study Region

The country was divided into three main zones based on temperature sum (Fig. 12.4), namely one with temperature sum >1,249 degree days called zone High and one with temperature sum between 850 and 1,249 degree days called zone Medium. Finally, zone Low was defined as those areas with a temperature sum of <850 degree days. These zones as well as their names may refer to tree growth and litter fall as well as humus growth, but the values for temperature sums were taken arbitrarily.

Humus-layer growth rate. Berg et al. (2009) obtained a clear demonstration of humus-layer growth rates by comparing data for the three main climatically different zones 'Low,' 'Medium,' and 'High' (Fig. 12.3). Using non-parallel lines for these zones, they illustrated that the humus layers were thicker in the southern third of the country with 7.19 cm (zone High) and 6.40 cm in zone Medium as compared to zone Low with 5.27 cm already before the measurements started. This initial thickness in humus layers is significantly different among the three zones.

All values from all four inventories are shown in Fig. 12.3, giving highly significant linear relationships with time, each zone having a linear relationship. Berg et al. (2009) assumed non-parallel lines in their model and obtained three linear relationships with the slope for zone High significantly steeper than for zones Low and Medium, which were not significantly different. The model was highly significant ($p < 0.0001$; F-test; $n = 83$) with $R^2 = 0.819$.

For 'all species,' the mean annual increase in humus-layer thickness is shown for the three zones based on temperature sum and differing in both climate and tree species composition (Fig. 12.4a). Zone High has a dominance of Norway spruce

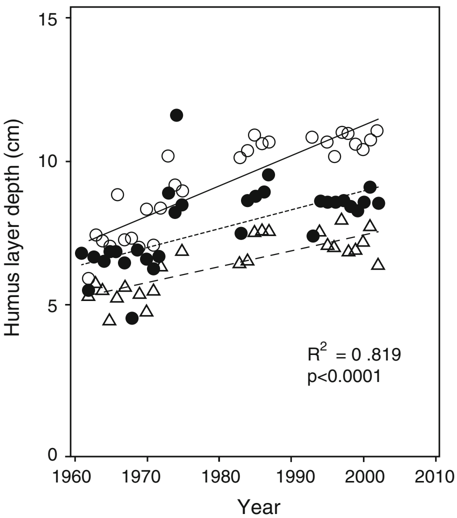

Fig. 12.3 Linear relationships for humus depth against time using non-parallel lines. Mean values for humus depth for each zone (*High, Medium,* and *Low*) are calculated on an annual basis, with each value being mean of 62–3,626 recorded average values. The slope coefficients are 1.05 mm (O——) for zone High, (● - - - -) 0.65 mm for zone Medium, (Δ - - - -), and 0.57 mm for zone Low. The *F*-test against non-parallel lines showed a significant result ($p = 0.0041$). From Berg et al. (2009)

and deciduous trees, zone Medium has Norway spruce and Scots pine without dominance, and zone Low has a dominance of Scots pine.

The estimated slope of 1.05 mm year^{-1} for zone High was significantly different from the estimates 0.65 mm year^{-1} of zone Medium ($p = 0.01$) and 0.57 mm year^{-1} of zone Low ($p = 0.002$). The difference between Medium and Low was not significant ($p = 0.60$).

There was a clear indication that this pattern is maintained over time. Thus, in zone High, the humus layers had increased to an average value of 11.39 cm in the last inventory (covering 41 years), which is significantly higher than in the first inventory (7.19 cm). In zone Medium, the increase was significant in the same 41-year period with an increase from 6.40 to 9.00 cm. Also, in zone Low, the increase was significant with an increase from 5.27 to 7.56 cm (Fig. 12.3). Based on this information, we can conclude that the measured humus-layer thickness has increased in general over large parts of Sweden in the studied period. The growth rates of the humus layer in the 41-year period ranged from c. 0.1 mm year^{-1} to > 1.6 mm year^{-1} among the 25 × 25 km grid cells. The pattern is patchy, but there is a general tendency to higher growth rates in the warmer zone as compared to the more northern with a lower temperature sum.

Areas with a decrease in humus-layer thickness were found in zones Medium and High (spruce) and for pine in the northernmost part of zone Low.

12.4.4.2 A General Tendency for Organic Layers to Increase with Time

In addition to the distribution of significant ($p < 0.05$) and non-significant relationships, Fig. 12.5 also gives areas without forest, indicated by white. Thus, in the

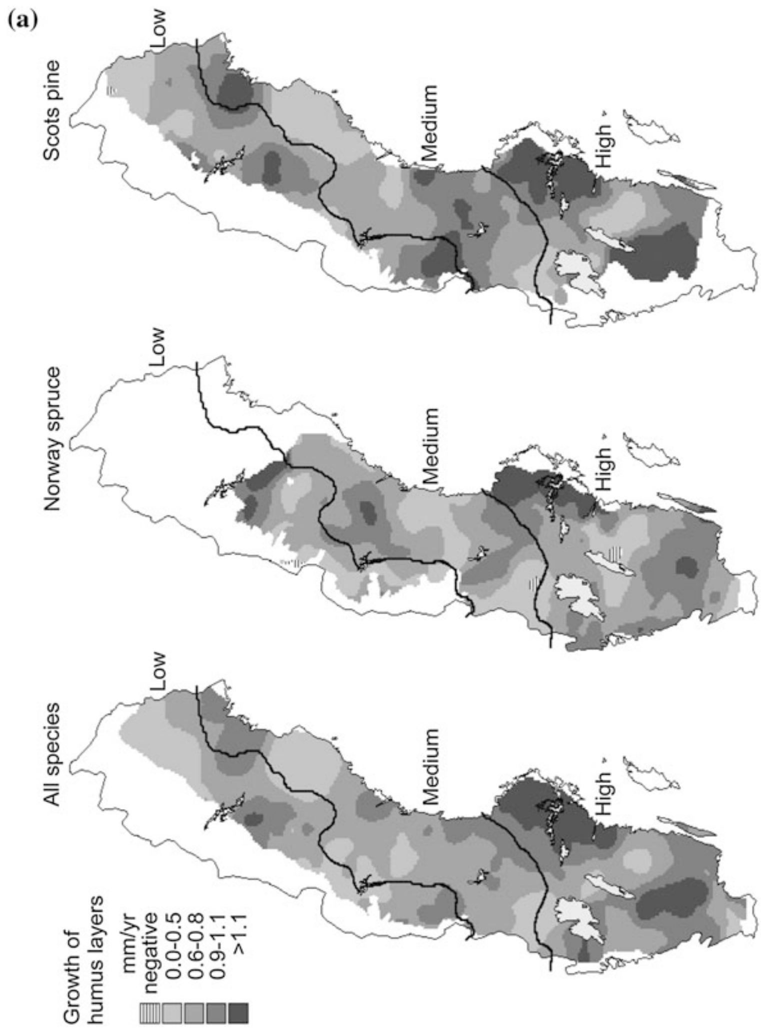

Fig. 12.4 The forested land was divided into three zones based on temperature sum, namely a zone with temperature sum >1,249 degree days called zone High, one with a temperature sum between 850 and 1,249 degree days and called zone Medium. Finally, zone Low was defined as those areas with a temperature sum of <850 degree days. There was also a subdivision of the area based on tree species. The map denoted 'all species' gives data for Norway spruce, Scots pine, and deciduous forests in mixed or in monocultural stands, while the maps denoted 'Norway spruce' or 'Scots pine' show areas where these species dominate. **a** Annual rate of increase in the humus layer. **b** Amount of carbon per mm humus layer and hectare (calculated from bulk density and C concentration). **c** Annual rate of carbon sequestration in the humus layer in Swedish forests in the period 1961–2002. (cf. Fig. 12.8). From Berg et al. (2009)

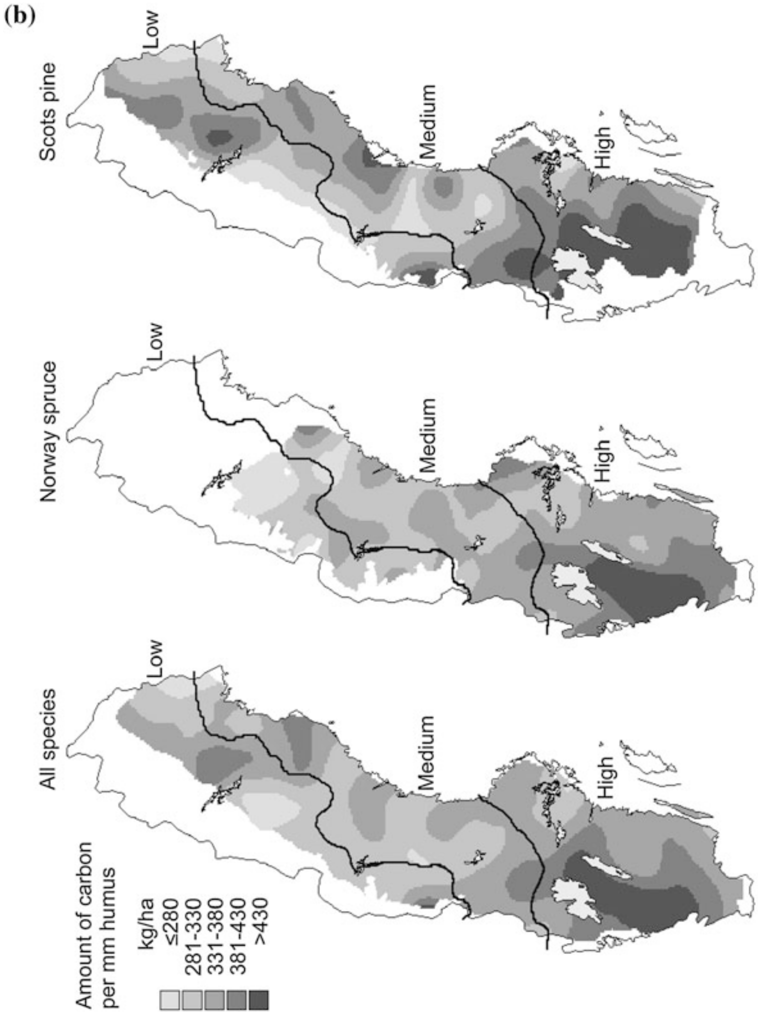

Fig. 12.4 continued

northwestern part is a mountain range with land classed as not forested. On low-nutrient soil in northern Sweden, there is too little Norway spruce planted to allow a separate evaluation. Likewise in the southwest, on richer soil and a wetter climate, Norway spruce dominates and very little Scots pine is growing.

There is a general tendency for the average thickness of the organic layer to increase with time. The areas with statistically significant increases in humus depth (cf Fig. 12.2) are distributed all over the country (Fig. 12.5). Within a dominant part of the country, the linear relationships, in some cases corrected by removing outliers, are statistically significant (Table 12.1, Fig. 12.5), providing evidence of a change in the humus-layer thickness.

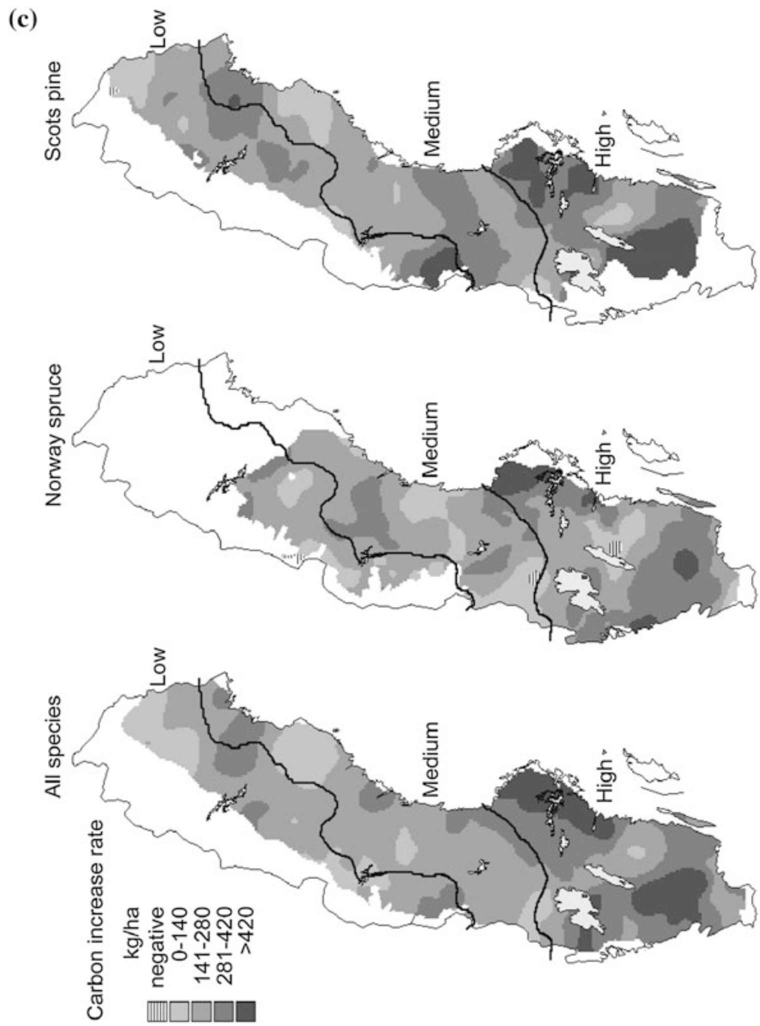

Fig. 12.4 continued

The three main areas with non-significant relationships in zone High (Fig. 12.5; all species) have long-term agricultural traditions, but since the 1960s, an extensive and ongoing afforestation is taking place. In zones Low and Medium, the relatively slow forest growth results in low litter fall and a low humus—accumulation rate that may explain the non-significant accumulation rates in these zones (Fig. 12.5). The ‘all species’ forest represents the whole forested area investigated, meaning that all combinations of species were evaluated together.

Table 12.1 Number of linear relationships for humus depth versus time for Scots pine and Norway spruce–dominated forests (basal area) plus forests encompassing all combinations of tree species

	Number of intersections (% in parenthesis)			C sequestration rate (kg ha^{-1} year^{-1})			
Tree species	Total	Significant	Non-significant	Mean	SD	Min	Max
All species	548 (100 %)	461 (84 %)	87 (16 %)	251	113	16	690
Positive relationships	548	461	87				
Negative relationships	0	0	0				
Spruce-dominated[a]	460 (100 %)	291 (63 %)	169 (37 %)	239	130	104	1,226
Positive relationships	456	291	165				
Negative relationships	4	0	4				
Pine-dominated[b]	505 (100 %)	422 (84 %)	83 (16 %)	283	158	34	1,187
Positive relationships	503	422	81				
Negative relationships	2	0	2				

The average C sequestration rate for each type is given. Cf. Fig. 12.4. From Berg et al. (2009).
[a] >70 % Norway spruce by basal area.
[b] >70 % Scots pine by basal area.

12.4.4.3 Humus-Layer Growth Rates Appear to be a Patchwork

The areas with high growth rates of the humus layers are found in Scots pine forests, whereas the humus layer of Norway spruce–dominated stands grows more slowly. We can compare this to the observation of Berg and Meentemeyer (2001) as recalculated by Akselsson et al. (2005) that foliar litter fall as a function of MAT is higher in Norway spruce forests (Table 12.2).

Scots pine. For pine-dominated forests, Berg et al. (2009) obtained a range of rates for humus-layer increase ranging from approx. 0.1 mm year^{-1}, mainly in the northern parts of the country, to 1.6 mm in the southeastern parts of zone Medium and northeastern parts of zone High (Fig. 12.4a). Pine forests in the central parts of zone High also had a humus layer with a growth rate above 1.1 mm year^{-1}. Areas with values in the range 0.9–1.1 mm year^{-1} were distributed all over the country. The relatively large white areas (Fig. 12.4a) indicate too few Scots pine-dominated stands to allow an evaluation, as pine is less common in coastal and maritime areas in the western parts of zone High. The small area with negative relationships in the northernmost part of zone Low (Fig. 12.4a) corresponds to the two intersections given for pine in Table 12.1.

Norway spruce. For forests dominated by Norway spruce, a range of annual humus-layer increase rates were seen ranging from a few negative values to a minor group with rates >1.1 mm year^{-1}, the higher rates applying for smaller areas. Like for pine, high rates were seen in the in the northeastern part of zone High (Fig. 12.4a), a former agricultural area. A small area with decreasing humus-layer thickness was found in the central parts of zone High, and a small area on the border between zones High and Medium, in all 4 intersections. The large white areas are due to a too low frequency of spruce forests to allow an evaluation.

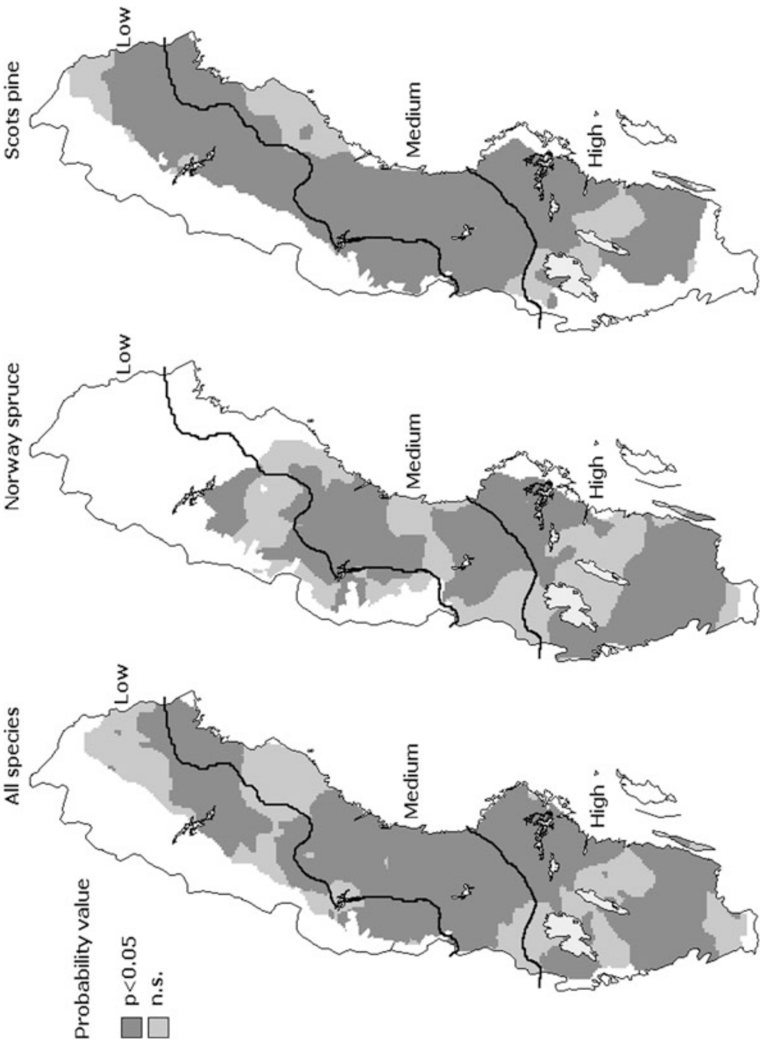

Fig. 12.5 Significant rates of increase in humus layer thickness ($p < 0.05$) as measured over 40 years. No decrease was statistically significant. The map denoted 'all species' gives data for Norway spruce, Scots pine, and deciduous forests in mixed or in monocultural stands, while the maps denoted 'Norway spruce' or 'Scots pine' show areas where one of these species dominate. (cf Table 12.1)

12.4.5 Calculations of Carbon Bulk Density in the Humus Layer

In the conversion of humus-layer growth (mm year^{-1}) to C accumulation rate (kg C ha^{-1} year^{-1}), bulk density and C analysis were used to calculate 'carbon bulk density' (kg C mm^{-1} humus ha^{-1}). For this purpose, Berg et al. (2009) used the bulk density and carbon analysis made at each sampling point and transformed the bulk density determined for humus to carbon density.

The carbon density varies over the country with a factor of 2 (Fig. 12.4b). The values for humus density used were in all cases based on local samples, and a clear variation was seen with species all over the country, with the highest density found in zone High.

12.4.6 Calculated Carbon Sequestration Rates and Some Patterns

12.4.6.1 General Comments to the Whole Case Study Region

In a third step, the humus growth rate (mm year^{-1}) was converted to increase in amount of carbon (kg C ha^{-1} year^{-1}) by simple multiplication with carbon bulk density (kg mm^{-1} ha$^{-1)}$ (Fig. 12.4c). Berg et al. (2009) thus converted the rate of increase in humus-layer depth to annual increase in C storage (C sequestration) (Fig. 12.4c). They obtained significant relationships (*t*-test; $p < 0.05$) for C sequestration rates, ranging mainly between 140 and 420 kg C ha^{-1} year^{-1}.

General patterns in high and low rates. The maximum rates for spruce-dominated and pine-dominated areas as well as for 'all species' were determined using the 25 × 25 km grid cells (Fig. 12.1; Table 12.1) and found to be 1,226, 1,187 and 690 kg C ha^{-1} year^{-1}, respectively. The average rate for the 'all species' group was 251 kg C ha^{-1} year^{-1} (SD = 113). This is also the rate that is representative as an average for the whole country.

Areas with low sequestration rates (lower than 140 kg C ha^{-1} year^{-1}) were almost exclusively found in zones Low and Medium (Fig. 12.4c). The main part of zone High had C sequestration rates above 281 kg C ha^{-1} year^{-1}, including an area with rates above 420 kg C ha^{-1} year^{-1} and only two small areas with rates below 140 kg C ha^{-1} year^{-1}. Again, the white zones indicate too few sampling plots to allow calculation of the sequestration rates.

Areas with high sequestration rates were larger in pine-dominated forests than in spruce-dominated ones. Pine-dominated forests in the northeastern and central parts of zone High had a very high sequestration rate of more than 420 kg C ha^{-1} year^{-1}.

Spruce-dominated forests showed a very different distribution as compared to pine-dominated forests, and there was only one main area with sequestration rates higher than 420 kg C ha^{-1} $year^{-1}$, located in the northeastern part of zone High. Two areas indicated a decrease, and a number of small areas had rates lower than 140 kg C ha^{-1} $year^{-1}$ (Fig. 12.4c).

In areas that had a significant humus accumulation rate (Fig. 12.5), the carbon sequestration rate ranged from less than 140 kg C ha^{-1} $year^{-1}$ to more than 420 kg C ha^{-1} $year^{-1}$. The maximum C sequestration rate in the same group was 696 kg ha^{-1} $year^{-1}$.

Relationship between net sequestration rate and temperature. The rate of C sequestration for 'all species' forests did not show any evident pattern over the country, although there was a positive linear relationship with the temperature sum ($R^2 = 0.29$; $n = 548$; $p < 0.0001$). The range in MAT for this region was c. −1.7–7.4 °C.

12.4.6.2 Carbon Sequestration Rates: Scots Pine versus Norway Spruce Forests

In the forested area studied, the two coniferous species, Scots pine and Norway spruce, dominate and we may evaluate the ecosystems as defined by this dominance. The average rates were 239 kg C ha^{-1} $year^{-1}$ (SD = 130) for Norway spruce-dominated forests and 283 kg C ha^{-1} $year^{-1}$ (SD = 158) for Scots pine-dominated forests.

Pine-dominated forests in the southern part of zone High showed a very high increase rate for stored carbon with >420 kg C ha^{-1} $year^{-1}$. Also, in pine forests in the northeastern parts of zone High, the increase rate was high, ranging from 281 to above 420 kg C ha^{-1} $year^{-1}$. The maximum C sequestration rates obtained were 1,226 and 1,187 kg ha^{-1} $year^{-1}$ for the forests dominated by spruce and pine, respectively.

Direct comparison of sequestration rates—Scots pine versus Norway spruce. It appears that Scots pine forests on the average can sequester more C in humus layers than those with Norway spruce. Berg et al. (2009) made a special comparison of carbon sequestration rates for the humus layer in pine-dominated forests as compared to spruce-dominated forests. A condition was that each 25 × 25 km grid cell used in the comparison (the same intersection; cf Fig. 12.1) must have both groups represented. They thus used only those 25 × 25 km grid cells in which plots with both kinds of domination were found and obtained 348 areas that fulfilled this condition. In these cells, the difference in C sequestration rate in the humus layers in Scots pine and Norway spruce forests was on average 71 kg C ha^{-1} $year^{-1}$ (SD = 161; $p < 0.0001$; paired *t*-test). The stands were located under similar climate conditions (temperature sum).

This comparison was made using only zones within which both forest types were represented by a sufficient number of plots to allow a comparison. Scots pine stands were located on soils typical for planting pine and Norway spruce on soils on which spruce normally is planted. The values calculated by Berg et al. (2009) thus represent sequestration rates under actual conditions integrating climate and soil properties but do not show the capacity of the pine or spruce ecosystem as such.

It is worth emphasizing that the values for ecosystems represented by single tree species, namely Scots pine and Norway spruce ecosystems, give very different values, namely 283 and 239 kg C ha^{-1} year^{-1} when determined for the whole forested area (Table 12.1). These two latter values are not average values for the species as such over the country but rather representative for two types of ecosystems and as such they may give some guidance to studies on the capacity of different humus layers to sequester carbon. The typical Scots pine system has a more open canopy, and the inflowing light allows rich ground vegetation that normally covers the ground completely. This may be, for example, mosses, heather, cowberry and bilberry or herbs, and grasses. In Norway spruce ecosystems, we normally find such dense canopies that the sparse light reaching the ground may support considerably less ground vegetation. In earlier chapters, we have discussed the possible humus contributions from woody litter components from the trees and from roots. We cannot exclude that the difference in ground vegetation may explain part of the difference between these two systems, especially as both have about similar amounts of woody components and Norway spruce in addition has a somewhat higher foliar litter fall.

If this reasoning holds, we may speculate that if such woody components as branches give very small inputs to the sequestered carbon, then this may be a similar contribution for both spruce and pine forests. The 239 kg C per hectare and year sequestered in Norway spruce forests may be realistic to compare to the average value of 180 kg C ha^{-1} year^{-1} as estimated by the limit-value approach based on needle litter fall only (below; Sect. 12.6).

12.4.7 Possible Sources of Error in Estimates of C Sequestration Rates

The present case study was made in forests that were and still are subject to management, including clear felling, site preparation, and ditching. This method to determine sequestration rates, in contrast to the theoretical limit-value approach, includes both inputs and losses and can thus be considered to give a net sequestration.

This means that the direct measurement approach registered a net increase in humus and carbon. Management practices such as site preparation and ditching initiate and stimulate microbial activity and increase humus decomposition and have been in practice since 1960s. In spite of this, there is a general annual increase in the humus layers of at least 0.57 mm (zone Low) and up to as much as 1.05 mm per year in zone High (Fig. 12.4a). Considering that there appears to be an effect of forest management on humus-layer thickness, the actual growth rate should be considered a net rate and probably an underestimate of the potential accumulation.

A technical error source in this method is also afforestation of old farmland. A certain plot that is registered as farmland is not included in the measurement system until it is planted. Directly after plantation, it is classified as forested land and humus-layer thickness are determined. With a minimum layer to be recorded, its contribution to the average for, for example, a 25 $\times$ 25 km grid cell thus results in a lower total increase. With several newly planted plots, this can cause a significant decrease (in average value) although all humus layers actually grow. Often, such farmland is planted with spruce which may explain the higher number of non-significant relationships for spruce.

12.5 Carbon Sequestration in Mineral Soil. Observations on a Regional Scale

12.5.1 Different Sequestration Patterns?

Sequestration in the mineral soil appears to go more slowly than the more readily measurable one in the organic layers, and on a regional scale, we have rather found inventories of amounts than indications of rates of change. It is not our intention to review the sequestration process in mineral soil, and we just intend to illustrate the connection between the primary and the secondary sequestration. We give a case study for the forested land of Sweden and may therefore directly compare the accumulation in the humus layer to that in the mineral soil.

The carbon bound in mineral soil has been suggested to be more protected than that in a humus layer. For example, mechanical disturbance and fire will primarily affect the organic layer. Still, there appears to be influences that may affect the carbon in the mineral soil, too. A recent report (Stendahl et al. 2010) adds useful information to our case study and appears to demonstrate that the primary and secondary sequestration may be related to tree species, and we have included these as an illustration.

We commented (above, Sect. 12.4.6) that the measured amounts of C in humus layers were significantly higher in pine-dominated forests as compared to those dominated by spruce.

New regional measurements on amounts in mineral soil in stands dominated by pine or spruce (Stendahl et al. 2010) over Sweden indicate a significantly higher storage in the mineral soil under spruce than pine ($p < 0.001$). Some parts of the sequestration pattern were similar and thus increased the amount of sequestered C with temperature sum (Fig. 12.6). This appeared to be most noticeable for pine. However, in both cases, the amount stored to 100 cm depth (O horizon plus mineral soil) increased with temperature sum. Stendahl et al. (2010) divided the sampling sites according to temperature sum and found that for each single group,

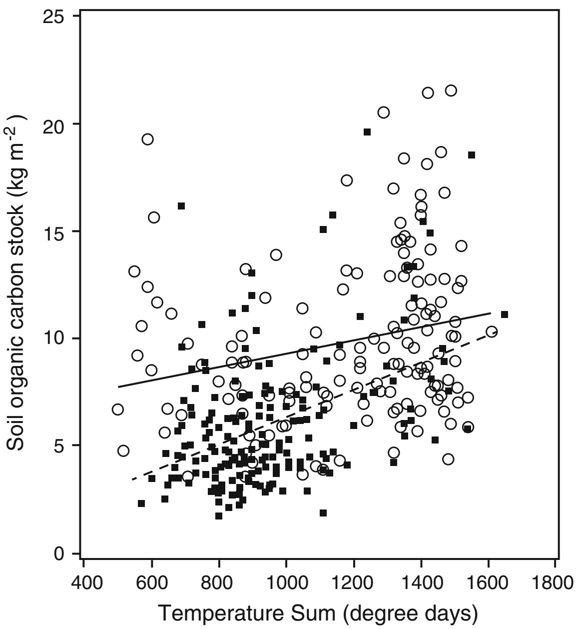

Fig. 12.6 Linear relationship between soil organic carbon (SOC) stock in the 0–100 cm soil layer and temperature sum for Scots pine plots (■ —) and Norway spruce plots (o —). The difference in slope was significant ($R^2 = 0.319$; $p < 0.001$). Figure from Stendahl et al. (2010)

spruce had higher sequestered amounts when both humus layer and mineral soil were considered (Fig. 12.7).

We thus cannot exclude that primary and secondary sequestration may be related to tree species. We have discussed this earlier (Sect. 11.7.1) for two systems (De Marco et al. (2010), namely with black pine and black locust. A simple reasoning thus gives that with Scots pine stands sequestering most in the humus layer and Norway spruce stands less, a higher total sequestration in spruce forests means a higher sequestration in the mineral soil.

12.5.1.1 Carbon Dioxide Budgets and a Case Study

For a limited area in zone High where Berg et al. (2009) measured high sequestration rates (Fig. 12.4c), it has been reported that the soil is a C source, as judged from net ecosystem exchange measurements of CO_2 in 1995–1997 (Valentini et al. 2000). With an estimated C sequestration in the humus layer of more than 420 kg C ha^{-1} year^{-1} for the area, losses of more than 1,000 kg C ha^{-1} year^{-1} from the mineral soil should occur to explain the source strength by Valentini et al. (2000). The authors attributed this unexpected loss of soil C to past soil drainage in the footprint area of their measurements. However, in a later study by Lindroth et al.

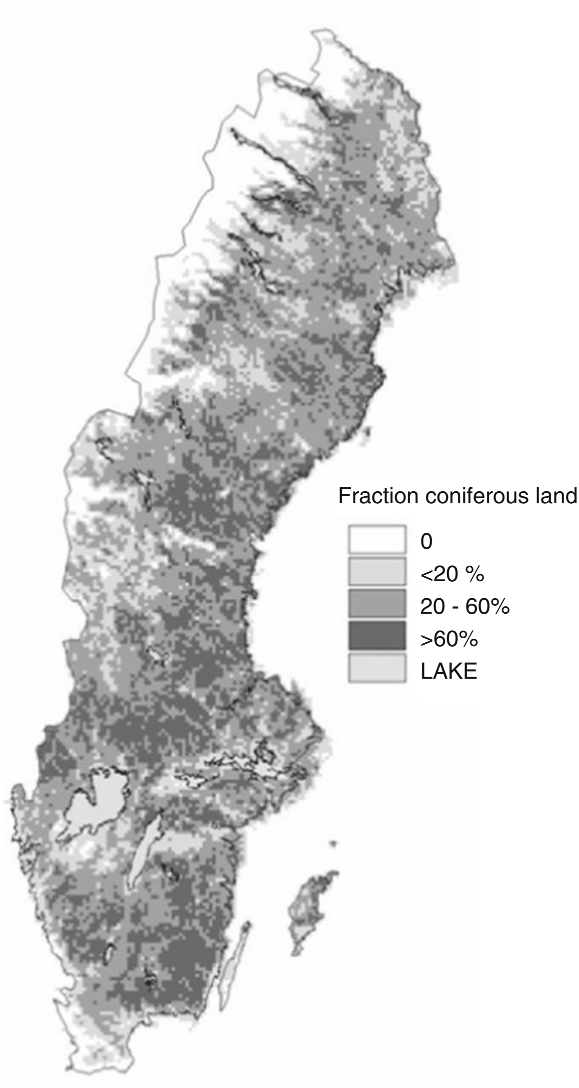

Fig. 12.7 Output from the geographical database giving the fraction of coniferous forest in Sweden with a resolution of 5 × 5 km. The basis for this geographical database is an IRS WIFS satellite image interpretation of the forested land (Mahlander et al. 2004). The satellite data have a resolution of 180 × 180 m, and the resolution of the database is 5 × 5 km. Thus, for each 5 × 5 km grid, the fractions of different land use classes are given as extracted from the satellite image. The database originates from Department of Forest Soils, Swed Univ Agr Sci., Uppsala. Figure from Akselsson et al. (2005)

(2008), using the same technique, this finding of a net loss from the soil (whole soil column) was repeated in Norway spruce stands at three further locations: two in our zone Medium and one in zone High. The obtained average net losses were c. 1,000 kg ha^{-1} year^{-1} (96–125 g m^{-2} year^{-1}; Lindroth et al. 2008) and consistent over two measurement years (2001–2002). The results of Berg et al. (2009) for the humus layer in the corresponding areas were 140–280 kg C ha^{-1} year^{-1} sequestered. Unless the soil has been disturbed at these investigated sites, resulting in an increased C mineralization, a possible conclusion would be that there is a heavy loss of carbon from the mineral soil. Lindroth et al. (2008) speculated that anomalously warm years were the reason for these unexpected losses, which appears to be in contrast to our finding of a positive relationship between temperature sum and C sequestration rate. However, the investigated plots were rather small. The authors give a radius of 100 m, which means a plot surface of 3.14 ha. With construction work and thus heavy soil disturbance plus active soil sampling work, at least part of the heavy carbon loss may be explained.

These contrasting differences in short-term and long-term results and methodologies underline the need for more detailed knowledge on SOM dynamics and stabilization and the need for comparison of several methods and approaches on the same locations.

12.6 Remaining Stable Fraction: A Theory and a Possible Regional Approach

12.6.1 Short Background

This section suggests an approach to estimate humus buildup or carbon sequestration by applying the concept of stable residue. We have used this approach before for a single site (Sect. 10.4; Table 10.3). Like for the case study above, we discuss just primary sequestration (Fig. 11.1). We describe the database that was used by Akselsson et al. (2005) and the expansion to a regional scale, the calculations of humus and carbon as well as the potential sequestration rates. After that, we discuss the effect of tree species on C sequestration rates and finally sources of error.

12.6.2 Geographical Database

In the database, all forested land is divided into (1) grid cells of the size 5 × 5 km, (2) forest classes, namely coniferous, deciduous and mixed forests, and clear-felled areas. An example of the information is given in Fig. 12.8, showing the fraction of coniferous forest in each 5 × 5 km grid cell. For each such cell, the fraction of different land use classes is given as extracted from a satellite image.

On the level of grid cell, there is also information about tree species. In the present case, the principal coniferous species were Scots pine and Norway spruce as well as two birch spp. as the dominant deciduous species. The fractions of Norway spruce and Scots pine in coniferous forests are known for each grid cell, as well as the fractions of birch and other deciduous trees in deciduous forests. The species that are lumped together and called ‘other deciduous’ are mainly common oak and common beech. For mixed (coniferous-deciduous) forests, the fractions of coniferous and deciduous are included in the database. The information on species

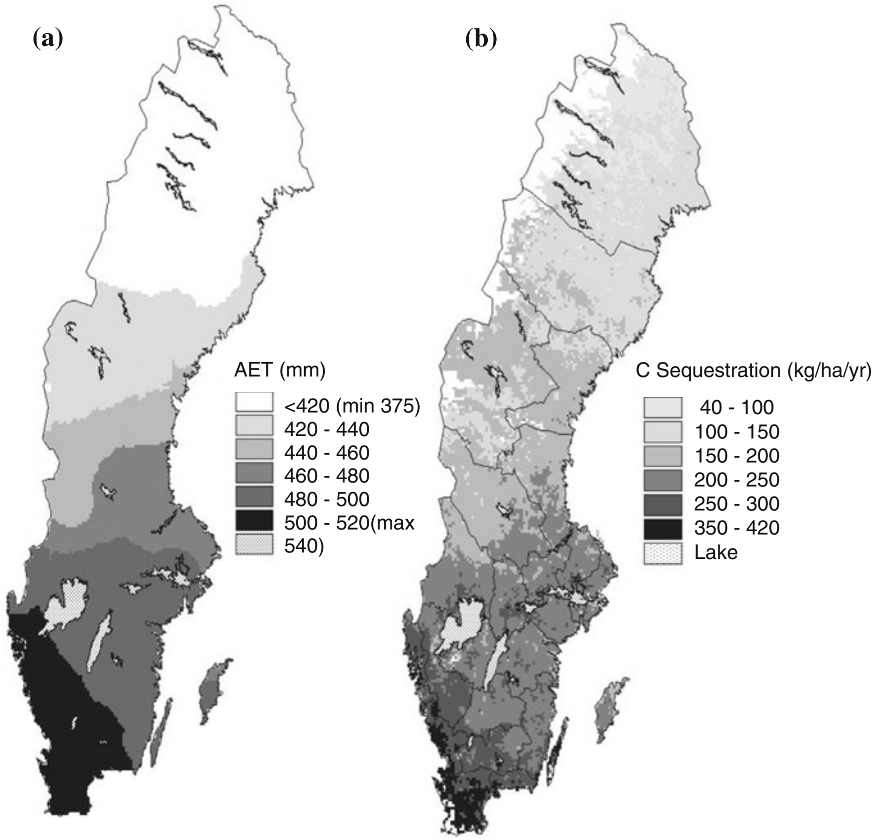

Fig. 12.8 **a** AET in Sweden, given as values for grid cells the size of 5 × 5 km. AET was calculated using the Thornthwaite and Mather (1957) water balance procedures and interpolated according to Kriging to cover 17,000 grid cells. **b** Carbon sequestration rates (kg C ha^{-1} $year^{-1}$) in the organic layers of forest soils in Sweden according to the limit-value approach. Values were calculated for the same 5 × 5 km grid cells as the AET climate index. Figure from Akselsson et al. (2005)

originates from the Swedish National Forest Inventory, and data from 15,318 specific sites were interpolated by Kriging. In this way, data based on specific sites were used to estimate values for all grid cells, giving each cell its fraction of coniferous and deciduous trees. Based on this, fractions of spruce, pine, birch, and 'other deciduous trees' were calculated for each grid and used for the further calculations.

Akselsson et al. (2005) used the climate variable actual evapotranspiration (AET), which is the sum of evaporation and transpiration in an ecosystem. Being a combined measure of heat and soil water, AET has shown to be a good predictor of various plant processes (Meentemeyer et al. 1982), for example litter fall, which is used in this study. An approximation of the field capacity of 300 mm for the root zone in the whole country is in accordance with previous work (e.g., Meentemeyer 1978; Meentemeyer et al. 1982; Dyer 1990) and makes it possible to use this climate variable on a regional basis. The first step for estimating AET for the grids was to calculate AET for 95 sites located all over Sweden that had detailed climatic data. Kriging interpolation to the 5 × 5 km grid cells was then performed based on these 95 sites, and the resulting values for AET were included in the geographical database. It may deserve to be pointed out that AET may have a wider generality as a climate variable than, for example MAT. In the case with Scandinavia and Northern Europe, however, MAT may fulfill the same purpose, as heat is limiting in this area (Berg and Meentemeyer 2002).

12.6.3 Expanding to a Regional Scale

To convert data for stable fractions of litter to a regional scale, Akselsson et al. (2005) used the linear relationships between foliar litter fall and AET. Three relationships were used, namely one for Scots pine, one for Norway spruce, and one in common for all deciduous species (Table 12.2). That was the factor they used for scaling up. It allowed for the estimation of litter input rates of each species or species group into each cell. In this step, MAT may be used as the litter fall in Northern Europe is linear to MAT (Table 12.2) and even gives a better linear model than AET. Beginning with litter fall and species composition, the limit-value (or stable residue) approach described earlier (cf. Sect. 10.4) can be applied to estimate potential carbon sequestration rates (below).

Table 12.2 Litter fall (kg ha^{-1} year^{-1}) as a function of AET (mm) for different tree species as well as groups of species in the forested land of Sweden

Tree species	Litter fall function				Source
	Intercept	Slope	R^2	*n*	
Norway spruce	−3,646.4 (642.1)	+12.09 (12.1)	0.47	13	(1)
Scots pine	−3,593.7 (508.6)	+11.03 (2.0)	0.48	35	(1)
Downy and silver birch	−785.5 (51.3)	+5.81 (1.8)	0.79		(2)
Other deciduous	−785.5 (51.3)	5.81 (1.8)	0.79		(2)

Standard error is given within parentheses. From Akselsson et al. (2005). Recalculated from Berg and Meentemeyer (2001).

[1] Berg and Meentemeyer (2001).

[2] Meentemeyer et al. (1982).

12.6.4 Calculation of the Buildup of Humus and Carbon

The annual foliar litter fall for each species group (Scots pine, Norway spruce, birch spp., and 'other deciduous') in a given 5 × 5 km grid cell was estimated separately using the equations based on AET (Table 12.2). The fraction of litter that would remain as stable matter was calculated as (100-limit value)/100 for each species and multiplied by the estimated litter fall. This gives the annual SOM buildup (cf. Berg et al. 2001) (Sect. 10.4) for each group of tree species. The values for SOM from all groups of species were added to give the average SOM buildup in each grid cell. In this first approach, Akselsson et al. (2005) used the same limit value for the dominant tree species, namely Norway spruce, Scots pine, and birch species. They took the general average value of 78.1% (a stable fraction of 0.239 for pine and spruce litter) and 63.8% for 'other deciduous' (stable fraction of 0.362).

The sequestration of carbon was calculated by multiplying the derived SOM buildup by the fraction of carbon in the foliar litter, and Akselsson et al. (2005) assumed a constant C fraction of 0.5. This simplification should be allowed since the calculations were based on falling foliar litter, in their case with a minimum of ash (less than 2% initially). The result is the C sequestration rate (kg C ha^{-1} year^{-1}) in the organic forest soil layers.

12.6.5 Potential Carbon Sequestration Rates

Potential C sequestration rates in the organic layers in forest soils in Sweden range from 40 to 410 kg ha^{-1} year^{-1} with an average of 180 kg ha^{-1} year^{-1} (Fig. 12.8b), as based on the limit-value concept. The general gradient gives decreasing C sequestration rates from the southwestern to the northern part of the country, mainly following the variation in AET (Fig. 12.8 a). In the southernmost and the southwestern parts, the C sequestration rates range between 300 and 410 kg ha^{-1} year^{-1}, in mid-Sweden, the levels are mainly between 150 and 200 kg C ha^{-1} year^{-1}, and in the northern parts, the sequestration is lower than 100 kg ha^{-1} year^{-1} with a minimum of 40 kg ha^{-1} year^{-1} at and north of the Arctic Circle. The annual C sequestration for the whole country is estimated to 4.8×10^6 t to be compared to 6.7×10^6 t as calculated from direct measurements in our first case study (Sect 12.4; Berg et al. 2009).

The general patterns of AET distribution and C sequestration rates are similar (Fig. 12.8). The AET ranges from 375 mm in the northern part of Sweden to 540 mm in the southwestern part with higher temperature and more precipitation. Because litter fall was related to AET and Akselsson et al. (2005) used a single average limit value for the three main tree species, AET has a major effect on carbon sequestration rates and this pattern should be expected. The approach of Akselsson et al. (2005) was based on foliar litter fall from mature stands and on limit values for decomposition of the foliar litter fraction. The rates given by them are thus only potential rates for the foliar litter fraction, without considering the effect of wild fires, site preparation, or other forest management practices. Further, the methods do not consider effects of non-foliar litters or stand age but give the potential growth rate for sequestered carbon from foliar litter only. Such a potential may have a value for determination of the capacity of the forest system as regards C sequestration.

12.6.6 *The Effect of Tree Species on Carbon Sequestration Rates in the Humus Layer*

Foliar litter fall is higher in Norway spruce than in Scots pine forests according to litter fall measurements (Table 12.2). In the present approach, this results in a higher annual mean C sequestration in Norway spruce than in Scots pine forests with 200 kg C ha^{-1} as compared to 150 kg ha^{-1}. The mean C sequestration rate in birch forests is the same as for pine, but the gradient over Sweden is more emphasized in pine forests (Fig. 12.9) with a wider range (60–260 kg ha^{-1}

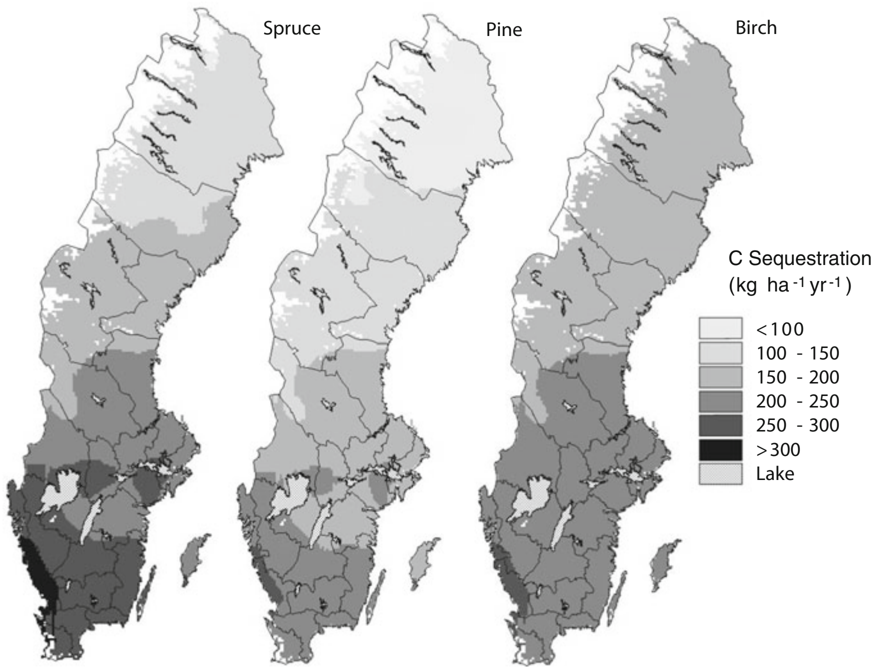

Fig. 12.9 Annual carbon sequestration rates in monocultural stands of Norway spruce, Scots pine, and birch spp. in different regions of Sweden. The sequestration rates were calculated using the limit-value method. Figure from Akselsson et al. (2005)

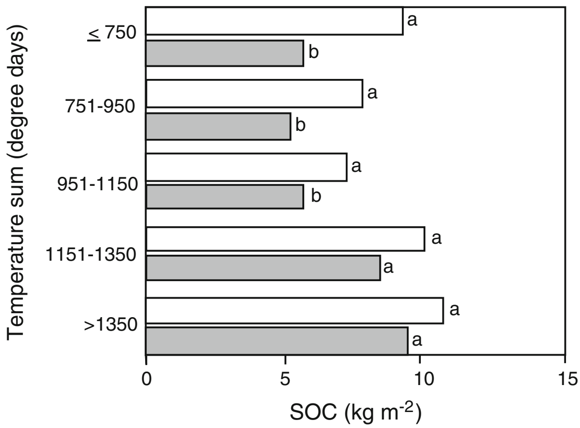

Fig. 12.10 Mean soil organic carbon (SOC) stock in the 0–100 cm mineral soil layer in plots of pure Norway spruce (*white bars*) and Scots pine (*shaded bars*) in different temperature sum regions in Sweden. Different letters indicate significant differences between plots with different tree species within each region ($p < 0.05$). Figure from Stendahl et al. (2010)

year^{-1}) than for birch (150–260 kg ha^{-1} year^{-1}). We may compare our first case study in which the C sequestration in humus layers was lower in spruce than in pine forests. Although the potential sequestration for spruce is higher than for pine, the actual amount in the humus layer is smaller, which may support different mechanisms for sequestration.

The litter class with 'other deciduous trees,' viz. common beech and common oak, is limited to the southernmost part of Sweden. It has the highest fraction of stable matter, 0.36 (average limit value 64 %), which leads to a higher C sequestration rate (about 400 kg ha^{-1} year^{-1}), than for Norway spruce, Scots pine, and birch litter, all with a stable fraction of 0.22. This effect can be seen in parts of southernmost Sweden (Fig. 12.9) where forests of common beech and common oak make up a significant fraction of the forested area, comprising up to 22 % of the stand biomass.

12.6.7 Sources of Error in the Limit-Value Approach

So far only foliar litter has been included in the calculations, and the potential rates of Akselsson et al. (2005) are thus potential rates for foliar litter only. Woody litter appears to have different decomposition kinetics, which at present makes it difficult to estimate its long-term contribution to C sequestration, which possibly is small. Further, for the different root and rhizome litter types, we still lack sufficient long-term basic information from decomposition studies to apply the limit-value concept. This also applies to moss, the litter formation of which is little known as is any limit value for decomposition.

There are further evident error sources. Akselsson et al. (2005) used foliar litter fall as a reasonable first approach, and the litter input is a primary error source, both as regards source and as regards rate. Their data for calculating litter fall were those available, which originated from mature stands. Smaller inputs following a clear-cut as well as the lower litter fall in the younger stands were not considered. The foliar litter fall is of course only one of the several fractions of the total litter fall, and in mature boreal stands of Scots pine and Norway spruce, foliar litter may encompass c. 70 % of the total litter fall in contrast to c. 100 % in very young stands (Mälkönen 1974). On the other hand, as pointed out by Flower-Ellis (1985) (see also Berg and Laskowski 2005), there are extremely few data on real total litter fall. The traditional litter trap for foliar litter is methodologically unsuitable to give correct recordings for 'total' litter fall, which means foliar litter plus, for example branch, twig, bark, and cone or acorn litter. This means that available data in the literature for 'total litter fall' in many cases simply may be incorrect and probably understated. Further, a general assumption on litterfall data is that the forest is relatively homogeneous, namely that it either has a naturally regulated high density or when comparing forests, the management is similar. For example, litterfall data are normally given as kg per hectare, and normally, tree density is not given but assumed to be similar among compared plots. A measure based on, for example, basal area which would reflect the biomass of the trees possibly could improve this.

Further, the input of root litter is very little known from a quantitative point of view as are the inputs of moss, grass, and shrub litter. The more open Scots pine forests support a higher growth of mosses and shrubs as compared to the more closed and darker Norway spruce forests. A calculation based on only foliar litter fall from the trees would thus underestimate the carbon sequestration in Scots pine forests as compared to Norway spruce. Further, in their approach, Akselsson et al. (2005) assumed that all the species sequestered C primarily in a humus layer.

The limit values reflect a relatively stable fraction of the foliar litter, but we simply know very little about the formation of stable material from woody litter and from fruits (e.g., cones and acorns) as well as of root litter. Available information suggests that at least for some tree species, the decomposition of woody litter may have a different pattern as compared to foliar litter. For litter from finer roots, different observations suggest that very small remains are left after decomposition under natural conditions.

In addition, effects of mineral soil Ca and P concentrations (Sect. 11.5) on long-term storage of humus in the O horizon were not considered in the approach taken by Akselsson et al. (2005) but could have a clear impact on the actual carbon sequestration rate.

12.7 Carbon Sequestration Rates in the Case Studies Compared to Quantitative Measurements in Single Stands and Chronosequences as well as among them

We have presented measurements taken in the organic layer, and they indicate a clear increase in spite of management practices. We have compared the rates calculated in the two case studies with more detailed and more long-term

Table 12.3 Comparison of measured sequestration rates for carbon as measured for specific stands in chronosequences or in other separate detailed and long-term investigations on podzolic soils. Only organic layers were considered

Location	Sequestration rate (kg C ha^{-1} $year^{-1}$)	Tree species	Source
Central Swedish Lapland	153	Mixed stands	(1, 5)
Central Sweden[a]	128	Scots pine	(1, 6)
South Finland	47	Norway spruce/Scots pine	(8)
Southwest Sweden	650	Norway spruce	(12)
Denmark	170–530	Different species	(2)
Denmark (Jutland)	350	Norway spruce	(11)
Denmark (Jutland)	80	Common oak	(11)
Scotland (UK)	353	Conifers	(10)
Wales (UK)	400	Sitka spruce	(9)
England (UK)	721	Scots pine	(13)
Central Netherlands	537	Scots pine	(3)
Central Germany	1,100	Norway spruce	(4)
Central Germany	320	Common beech	(4)
Central Germany and the Alpine region[b]	190–470	Norway spruce	(7)

[a] Extremely nutrient-poor stand.
[b] Six stands of Norway spruce.
1. Berg et al. (2001), 2. Vesterdahl and Raulund-Rasmussen (1998), 3. Estimated from Tietema (2004), 4. Berg (2004) as recalculated from Meesenburg et al. (1999) and Maiwes et al. (2001), 5. Wardle et al. (1997), 6. Staaf and Berg (1977), 7. Thuille and Schulze (2006), 8. Peltoniemi et al. (2004), 9. Gundersen et al. (2006) 10. Billet et al. (1990), 11. Vesterdal (2003). 12. Vesterdal (2006). 13. Ovington (1959).

measurements for Sweden and the other Nordic countries that are reasonable to use for a comparison (Tables 12.3, 12.4). The detailed measurements are taken at single sites, and we compare them with the calculated rates for the corresponding region.

The site measurements were taken by resampling of humus layers over several decades or inferred from studies of chronosequences of stands including some afforestation sites where the organic layers were built since planting of the stand. For natural, unmanaged stands (mixed species) in Swedish Lapland (Wardle et al. 1997), the mean rate (153 kg C ha^{-1} $year^{-1}$) was similar to that estimated for the surrounding investigated area with a range of 141–280 kg C ha^{-1} $year^{-1}$, ‘all species’ group. For the same area, the case study using stable residue obtained a rate of 100–150 kg C ha^{-1} $year^{-1}$ (Table 12.4). For central Sweden, the measured rate in a very nutrient-poor Scots pine forest (128 kg C ha^{-1} $year^{-1}$) was close to the range estimated for pine forest in that area (<141 kg C ha^{-1} $year^{-1}$). The stable residue approach gave a range of 150–200 kg C ha^{-1} $year^{-1}$ (Table 12.4).

For southernmost Sweden, we compared our estimated values with measurements taken in southern Sweden and in the areas at the same latitude and with a

Table 12.4 Comparison of measured carbon sequestration rates (humus layers) in a case study and a limit-value approach for the forested land of Sweden and detailed local studies

Location	Measured other studies (kg C/ha/year)	Stable residue approach	Direct humus determinations
General comparison			
Central Swedish Lapland	153	100–150	141–280
Central Sweden	128	150–200	<141
Southwestern Sweden	650	250–420	280–420
East Denmark	170–530	250–420	141–280
Average values			
Whole country	nd	180	251
Scots pine ecosystems	nd	150	283
Norway spruce ecosystems	nd	200	239

Table from Berg et al. (2009). nd stands for not determined.

similar climate in Denmark and found that the estimated values of Berg et al. (2009), viz. 141 to more than 420 kg C ha^{-1} year^{-1}, were in the same range as the measured 170–530 (east Denmark) and 650 kg C ha^{-1} year^{-1} in south Sweden (Table 12.4). The stable remains approach gave a range from 250 to 420 kg C ha^{-1} year^{-1}.

Carbon sequestration rates for southern Germany and the Alpine region at sites with temperature and precipitation ranges similar to those found in south Sweden and a few sites in Scotland and Wales are reported to range between 200 and 500 kg C ha^{-1} year^{-1} and are thus comparable with our values (Table 12.3). At one Scots pine site in south Germany, no change could be detected after 22 years although a nearby site showed an accumulation of 200 kg C kg ha^{-1} year^{-1} over 30 years (Prietzel et al. 2006).

Measurements in a chronosequence of Scots pine in central Holland gave a sequestration rate of approximately 540 kg C kg ha^{-1} year^{-1}, thus somewhat higher than the highest values found by us for east-central Sweden. In central Germany, rates of 1,100 and 320 kg C ha^{-1} year^{-1} have been found for Norway spruce and common beech stands, respectively (Table 12.3), indicating a difference between species on the same soil.