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Carbon and nitrogen stocks in Norwegian forest soils – the importance of soil formation, climate and vegetation type for organic matter accumulation

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23

24 **Abstract**

25 Relationships between soil C and N stocks and soil formation, climate and vegetation were
26 investigated in a gridded database connected to the national forest inventory in Norway. For mineral
27 soil orders C and N stocks were estimated to 11.1-19.3 kg Cm⁻² and 0.41-0.78 kg Nm⁻² declining in
28 following order Gleysolic>Podzolic>Brunisolic>Regosolic. Organic-peat type soils stored on average
29 31.3 kg Cm⁻² and 1.10 kg Nm⁻², while shallow Organic Folisols, on average stored 10.2 kg Cm⁻² and
30 0.34 kg Nm⁻². For Norway's 120 000 km⁻² of forest the total soil C stocks was estimated to 1.83 GtC
31 with CL95% 1.71–1.95 Gt C. Podzolic soils comprise the largest soil group and they store
32 approximately 50% of the forest soil C. Sixty percent of the soil C stock in Podzolic soils was stored in
33 the mineral soil, and increase with temperature and precipitation. Poorly drained soil types store
34 approximately 47 % of the total forest soil C in Norway. Soils with water saturation have large C
35 stocks mainly in the forest floor suggesting that they are more susceptible to forest management
36 and environmental change. Soil C stocks under pine and spruce forest were similar, though pine had
37 larger C stocks in the forest floor while spruce had the highest C stocks in the mineral soil
38 compartment. C stocks in forest floor increase from dry to moist ground vegetation, while ground
39 vegetation nutrient classes reflect C and N stocks in the mineral soil better.

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41 Key words: Forest soil, carbon, soil formation, pedology, Norway, Boreal forest,

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43 Introduction

44 Boreal forests are an important part of the global carbon (C) cycle and are considered to be
45 moderate to strong sinks for atmospheric C, depending on forest management, forest fire, site
46 fertility and local climate e.g. ([de Wit et al. 2015](#); [Karhu et al. 2011](#); [Liski et al. 2002](#); [Luyssaert et al.](#)
47 [2010](#); [Schimel et al. 2001](#); [Schulze et al. 1999](#)). The contribution of the soil to the total forest C
48 balance is uncertain, partly because of a general lack of representative forest soil data, as
49 comprehensive soil monitoring is only rarely included in forest inventory programs ([Callesen et al.](#)
50 [2015](#); [Goodale et al. 2002](#); [Van Cleve and Powers 1995](#)). The uncertainty and lack of data on soil
51 contrast with its importance as a C pool. Boreal forest soils including the forest floor have been
52 reported to store two to five times that of the forest biomass ([Bradshaw and Warkentin 2015](#);
53 [Goodale et al. 2002](#)) and the organic matter of boreal forest soils is more sensitive to warming than
54 soils of other climatic zones ([Davidson and Janssens 2006](#)). Our ability to predict consequences of
55 future climate changes depend in part on our understanding of the distribution and controls of C
56 stocks in soils ([Deluca and Boisvenue 2012](#)). Several studies have explored the possibility of using
57 soil inventories and taxonomic units to estimate soil organic C stocks e.g. ([Grossman et al. 2001](#); [Guo](#)
58 [et al. 2006](#); [Shaw et al. 2008](#); [Tarnocai 1998](#)) and concluded that this may be a good approach to
59 estimate and understand the mechanisms regulating soil C stocks ([Shaw et al. 2008](#)). The advantage
60 of using soil formation and pedogenic horizons in the C stock assessment is the gain of additional
61 information on the nature of the soil organic matter and causal connections between environment
62 and C dynamics. Internationally used soil classification systems reflect soil development, and
63 organic matter is one of the key mediators in soil development ([Van Cleve and Powers 1995](#)).
64 Processes involving organic matter lead to horizons with distinct chemical, physical and biological
65 properties. The soil organic matter in both surface and subsoil are specific to different pedogenic
66 processes, organic C is therefore, one of the major differentiation criteria in all modern soil
67 classification systems e.g. Soil Taxonomy ([Soil Survey Staff 1999](#)) and World Reference Base for soil
68 resources , ([WRB 2015](#)). Most soil classification systems emphasize subsurface properties as these

69 are considered more stable, and a change in land use e.g. from forest to cultivated land should not
70 influence the higher level classification. Soil classification should therefore not be expected to reflect
71 properties of the surface horizons of forest soils sufficiently to provide a good and reliable predictor
72 of C stocks in these soil layers. The Canadian soil classification system may, however, be an
73 exception as also surface horizons may be diagnostic ([Agriculture Canada Expert Committee on Soil](#)
74 [Survey 1987](#)). In the early 1980's the Canadian soil classification system was chosen as the most
75 appropriate modern soil classification system to adapt to Norwegian conditions. Similarities in
76 climate, parent material, and pedogenic age, in addition to having a nomenclature close to the old
77 Scandinavian system ([Frosterus 1923](#)), favoured this choice.

78

79 No soil map of Norway exists detailed enough to provide any reliable estimate of soil carbon in
80 Norway. Only crude estimates of total C stocks in Norwegian forest soils have been published
81 previously e.g. ([de Wit and Kvindesland 1999](#); [Kjonaas et al. 2000](#)). Though some publications have
82 discussed C stocks in Norwegian forest soils in relation to parent material, climate e.g. ([Callesen et al.](#)
83 [2003](#)) and forest management ([Nilsen and Strand 2008](#); [Nilsen and Strand 2013](#)) these are not
84 representative for the Norwegian forest area in general. During the first forest inventory initiated by
85 the International Co-operative Program on Assessment and Monitoring of Air Pollution Effects on
86 Forests (ICP-forest) Norway compiled a forest soil database containing 1040 detailed soil profile
87 descriptions down to 1 m or to bedrock with accompanying chemical and physical analysis. This
88 database is unique as i) it includes all drainage classes ii) it covers the major Norwegian forest
89 vegetation types and climate and iii) the soil pits were chosen in a systematic manner giving soil
90 profiles that were representative for the forest plots. This offers a potential to explore C stocks in
91 Norwegian forest soil according to pedology, as well as relationships to gradients in climate,
92 vegetation, parent material and topography. Our main objective for this study is to provide an
93 estimate of the C stocks in Norwegian forest soils, and the closely related N stocks, stratified

94 according to soil taxonomic units. Additionally, we examine sources of uncertainty and quantify the
95 uncertainty of the soil C stocks estimates at the scale of the soil profile and taxonomic unit. Further
96 we use the taxonomic stratification to explore the relationship particularly between the soil C stock,
97 climate, vegetation, drainage and soil depth. Finally we estimate total soil C stocks for the forest
98 area of Norway.

99

100 **Materials and Methods**

101 Forested area of Norway

102 Norway spans over 13 degrees of latitude, and comprises an area of 324 000 km². Due to the Gulf-
103 stream and strong influence by westerly winds the climate is milder than expected compared to
104 other countries on similar latitudes. Frequent and sharp changes in topography in addition to
105 altitudes spanning from 0 – 1000 meters above sea level over relatively short distances, contribute
106 to considerable variation in the local climate. Excluding mountain areas, mean annual air
107 temperatures (MAT) in Norway vary from -3.1 to 7.7 °C ([Aune 1993](#)). Highest and lowest mean
108 annual temperatures are found in the coastal southern and western Norway and in the inland
109 eastern and northern Norway, respectively. Mean annual precipitation (MAP) ranges from 278 to
110 3575 mm (average for the period 1960- 1990). Coastal western Norway receives the most and inland
111 areas of eastern and northern Norway receive the least precipitation ([Forland 1993](#)). Most of the
112 forested areas in Norway have parent material of till (morainic) or glacio-fluvial origin though areas
113 of marine deposits, colluvium and peat are also found, all deposited after the last Ice age (<12000
114 years). The dominating till and glacio-fluvial parent material is generally transported over short
115 distances and is of gneissic, granitic or quarzitic origin giving stony and coarse textured soils.

116

Approximately 37 % of Norway's land area is forested, 120344 km² according to the Norwegian Environmental Agency (2015). Of the total land area productive forest makes up 26.7 % and the remaining forested area is unproductive forest and mountain-birch forest (Granhus et al. 2012). Approximately 70 % of all forest is below 500 meters above sea level (m.a.s.l.). Most forest is found in east and central Norway, Figure 1. Dominating tree species are Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.), and birch (mainly Downey birch (*Betula pubescens* (L.) Ehrh.) and European white birch (*Betula pendula* Roth.)). Spruce dominates the productive forest area (> 1 m³ ha⁻¹ year⁻¹, canopy cover > 10%) while deciduous forest dominate in low productivity forest (<1 m³ ha⁻¹ year⁻¹, canopy cover <10%). (Granhus et al. 2012). Approximately 6.6 % of the productive forest in Norway is characterised as old forest, that is forest that is considerably older than recommended harvest age for the given forest stand (Granhus et al. 2012).

The forest soil database

For this study an existing land representative forest soil database, collected in connection with the ICP forest monitoring program level 1 sites was used (Lorenz 1995). This database covers forest sites in a grid system (9*9 km) from 5° west to 30° east, 58° south to 70° north and from 2 to 1190 meters above sea level (m.a.s.l.). The soil profile sampling points follow the forested area, thus there are few data from the northernmost county (Finnmark), central mountain areas and the coastal areas in general, see Figure 1.

A total of 1040 soil profiles were described, sampled and analysed between 1988 and 1992 (Esser and Nyborg 1992). Since that time, no other systematic area representative forest soil surveys have been conducted in Norway. Locations for soil profiles were chosen systematically, measuring 5 m northward from the centre of each forest monitoring plot then turning 90° clockwise avoiding trees,

141 stumps and boulders until a location representative for the plot was found. Soil profile descriptions
142 were done according to standardized procedures ([Sveistrup 1984](#)). Soil samples were taken from
143 each described horizon in the soil pit. Additional 5 - 10 samples were taken with an auger, spread
144 across the plot, and bulked together with the same horizons as described in the soil pit. Soil for
145 chemical analysis was subsampled from a mixture of soil from the pit and from the bulked sample
146 ([Esser and Nyborg 1992](#)). In addition to information on soil properties and classification, the
147 database contains general area data, information on topography and landform, forest (dominating
148 tree species, stand age, forest maturity class (1 to 5 where 5 is mature), site index (stand height at
149 age 40 years) and ground-vegetation (moisture classes 1=dry, 2= medium, 3=wet; nutrient classes
150 1=poor, 2=medium, 3=rich), parent material, drainage (drainage classes from excessively well
151 drained=1 to very poorly drained=13) and groundwater relationships. Many of the field observations
152 are registered as class-variables, and where appropriate, they have been converted to numerical
153 values (mean class value). This applies for slope, aspect, stone and gravel content. Field
154 determinations of texture classes for the fine earth fraction were done for all mineral soil horizons.
155 Laboratory analysis of particle size distribution was only done for one horizon from each profile, two
156 if there were lithological discontinuities. The soils were classified according to the Canadian soil
157 classification system and standard chemical analyses were performed as required ([Agriculture
158 Canada Expert Committee on Soil Survey 1987](#)). All sampled soil horizons were analysed for organic
159 total C and N by dry combustion using a Perkin-Elmer 2400 CHN element analyser. The total C
160 analysis was interpreted as organic C, as all Norwegian forest soils have acidic pH and therefore is
161 not expected to contain inorganic C. The database contains no information on soil bulk density.
162 Climatic data included mean annual precipitation (MAP) and mean annual temperature (MAT) and
163 length of growing season given as the sum of days with a 24-hour average temperature of at least
164 5 °C. These were calculated for each forest inventory plot based on standard normals (1961-1990)
165 and adjusted according to plot elevation, as provided by the Norwegian Meteorological Institute.

166

167 Soil classification

168 The soil profiles were classified following the Canadian system of soil classification, in which the
 169 order level is based on similarities in soil profile development, and reflects major soil forming
 170 processes. The second level, the great group, reflects differences in development of the dominant
 171 soil forming process and the third level, the sub group, reflects intergrades towards other soil orders
 172 and special features not related to the dominating soil forming process ([Agriculture Canada Expert](#)
 173 [Committee on Soil Survey 1987](#)). Five soil orders, 15 great groups and 45 subgroups were present in
 174 the Norwegian forest soil database in addition to sites registered as non-soils (soils < 10 cm thick)
 175 (Table 1). In the present study, the soil taxonomic units were grouped according to processes
 176 believed to be important for accumulation and stabilization of organic matter in the soil. The
 177 following processes were identified as important 1) water saturation 2) podzolization 3)
 178 brunification 4) drought and root restriction due to restricted effective soil depth (Table 1).

179

180 Calculation of C stocks in soil profiles

181 Definitions similar to those of Tarnocai ([1998](#)) were adopted: Total C stock in kilograms per square
 182 meter (kg m^{-2}) expresses the amount of C in a one meter square column of a soil. The soil C stocks
 183 per horizon were calculated using equation 1. The C stock per profile was calculated using equation
 184 2, summing the C stocks for all the horizons in the profile, down to the full depth of the profile,
 185 however a cut-off depth at 100 cm was used when calculating the profile carbon stock. Only 2 % of
 186 the profiles were described and sampled to depths greater than 100 cm.

187 Horizon:

$$188 \quad C_{\text{stock}} = BD * C_{\text{cont.}} * T * CF_{\text{coarse}} \quad (\text{equation 1})$$

189 Profile:

$$190 \quad C_{\text{stock profile}} = (C_{\text{stock, horizon 1}} + C_{\text{stock, horizon 2}} + \dots + C_{\text{stock, horizon n}}) \quad (\text{equation 2})$$

191

192   Where:

193   BD = bulk density (kg m^{-3})

194   C_{cont} = organic C content (kg kg^{-1})

195   T = thickness of horizon (m)

196   CF_{coarse} = correction factor for stone and gravel content = $1 - (\text{gravel vol. \%} + \text{stone vol. \%})$

197   /100

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199   For soils classified as mineral soils (Podzolic, Brunisolic, Regosolic and Gleysolic) the distribution of C
200   stock between the LFH horizons and the mineral soil was expressed as the percentage of the total C
201   stored in the mineral soil compartment for each profile.

202

203   Where data essential for calculating horizon C stocks were lacking we estimated the missing data
204   using different approaches. For bulk density data this applied to all horizons. For mineral soil
205   horizons we used a pedotransfer function developed by Honeysett and Ratkowsky ([1989](#)) and
206   parameterized by Baritz et al. ([2010](#)) using a large European forest soil database.

207        $BD = 1 / (0.564 + 0.0556 \times \text{SOM \%})$. (equation 3)

208   Where SOM is soil organic matter and set to be equal to $1.724 \times \% \text{C}$

209   A separate database for published and unpublished data on organic and mineral soils from
210   Norwegian forest soil ([de Wit and Kvindesland 1999](#)) contained measured bulk densities from forest
211   soil horizons. Comparisons between measured and estimated bulk densities for this separate bulk
212   density database showed that the Baritz et al. ([2010](#)) pedotransfer function was suitable for
213   estimating the Norwegian bulk densities for mineral soil horizons ($r^2=0.65$, slope=0.89) though
214   slightly underestimating the measured bulk densities. No satisfactory pedotransfer function could be

made for the organic horizons, instead the median bulk density values from the separate soil data base (785 organic horizons) were used to estimate the bulk densities of the organic horizons with equivalent horizon designations.

Information on stone content was missing from 6 % of the mineral soil horizons and 15 % had no information on gravel content. As the stone and gravel content in the database were registered as class variables, these were converted to the mean of the lower and upper class limit. Both gravel and stone classes were given as volume percent per horizon: four gravel classes (<20, 20-50, 50-90 and >90), and seven stone classes (<0.1, 0.1-2, 2-5, 5-10, 10-20, 20-40 and >40). Where nothing else was stated, we assumed that there were no stone or gravel in organic horizons. If one or more of the mineral soil horizons within a profile lacked gravel and stone information and no shift in lithology was indicated, we used the average of the above and below horizons. If only one horizon contained information on gravel and stone content this was used for all mineral soil horizons. If all information on coarse material was missing from the profile, the median of all coarse fraction data in mineral soil horizons of the same parent material was used.

Ten percent of all horizons had no information on C concentration. These were mostly thin horizons or transitional horizons. We estimated the missing values by applying the mean of the horizons immediately overlying and underlying the horizon. Fifteen percent of the profiles had no exact information on the thickness of the deepest horizon, in this case the lowest horizon was assumed to have a thickness of 20 cm.

Simulated uncertainties for typical soil profiles

The pedological approach to soil C stock assessment means that systematic variation in the C stock data are assigned to master horizon type and a layer volume defined by horizon thickness measured

in the profile. Uncertainty, i.e. random error in the soil organic C estimates in each profile arises from stone and gravel content, which is given in class intervals of non-uniform size, from soil sampling and the following C concentration determination in the fine earth fraction, and from the bulk density assumptions made. The C stock of a given profile is, depending on the number of horizons described, the sum of 4-7 summed products (equation 2). Each soil layer is a product of the four factors; layer volume, stone and gravel content, bulk density and C concentration (equation 1).

The uncertainty arising from the stone and gravel assessment as a class variable with increasing interval sizes, and the bulk density assumptions based on the pedotransfer function (equation 3) was simulated for each horizon. A relative error of 2 % was used for measured C concentrations between 1 and 10 % while the relative error was doubled (± 4 %) for concentrations lower than 1 % and for concentrations larger than 10 % C. The reason for differentiating the relative error for the C concentration is that random errors for e.g. sampling will be larger both at low concentrations (in laboratory) and for high concentrations (during field sampling). For the bulk density relative errors of ± 5 , 10 and 20 % of the simulated bulk density was assumed. For the coarse fraction two approaches were tested using either 1) uniform distribution within the field registration class limits for gravel and stone content, so that each value in the interval had the same probability, or 2) the mid-class stone content from the field registration class, e.g. the stone content would be 15 % in the 10-20 % class.

Ten typical soil profiles from the forest soil database were chosen for the simulation of C stock estimate uncertainty (Table 2). These profiles had C stocks close to the median of the soil group they represented. The horizon data from each of these profiles formed the background data for the Monte Carlo (MC) simulation. The MC simulations were run 1000 times per profile (with calculations

by horizon) and the sum of the C stock for the representative profiles was calculated. The mean and standard error of the resulting C stock simulations for each profile were calculated.

Estimates of total forest C stocks

Estimates of forest soil C stocks (C in soil) were calculated by multiplying the Ismean C stocks with corresponding area estimates for each soil type and expressing this as gigaton carbon (Gt C). The uncertainty estimates were done by two different methods; i) one for each of the soil groups where we expect the uncertainty regarding the areas will be larger for the less frequently occurring soils; ii) a second method for the National forest soil total C stock using the same area uncertainty as that applied by the national forest inventory ([Norwegian Environment Agency 2015](#)).

Areas for each of the soil groups were found based on the assumption that the distribution of soil types in the database represent equivalent proportions of soil cover in the forested area in Norway. The standard error (SE) for each soil group area was found by first calculating the standard error connected to the proportion (p) of each soil group $SE = \sqrt{p(1-p)/(n-1)}$ where n = number of total observations. This standard error connected to the proportion was thereafter used to calculate the coefficient of variances (CVarea) for the corresponding area. The coefficient of variances of the soil group mean SOC estimate (CVSOC) was calculated from the SE of the simulated profiles and the group Ismean (see Table 5, Table 3). Assuming that errors between factors are uncorrelated we then calculated $CV_{total} = \sqrt{(CV_{area})^2 + (CV_{SOC})^2}$ for C stocks of each soil group ([Snedecor and Cochran 1967](#)).

The total C stocks in Norwegian forest soils were calculated by summing the C stocks estimate based on the Ismean for each of the soil types as described above. The uncertainty estimates for the total

forested area of Norway (CV for total forested area) was set to 2 % as based on registrations by the National forest inventory ([Norwegian Environment Agency 2015](#)). The variance of the total SOC stock was found summing the weighted group variances and from this a CV of 2.8% was calculated. The total uncertainty, was then $CV = \sqrt{(2)^2 + (2.8)^2}$ equalling 3.4%. Finally the mean total forest soil C stock and confidence intervals (CL95%) were regulated downward with by 8% as a consequence of the skewed mean.

Statistical analyses

Differences in soil C stocks between the different soil groups were analysed by one-way ANOVA. Multiple comparisons of means between the different classes were done using the Students-Newman-Keuls multiple range-tests on all main effects ([SAS Institute 1990](#)). Estimates of 95 % confidence limits on least significant means were made using the LSMEANS procedure. All correlation analyses were done by the non-parametric Spearman method in the CORR procedure of the SAS software package ([SAS Institute 1990](#)). The Monte Carlo simulation was run using the R package “foreach” (R 3.1.2) ([R Development Core Team 2010](#)).

Results

Total C and N Stocks and C:N-ratio

The largest amounts of C were found in the soils dominated by water saturation processes. These comprise 32 % of the soils in the database (Table 3). Among these, the largest C stocks were in the Organic-wet soils, and declining from Gleysolic, gleyed Podzolic to gleyed Brunisolic. Among the self-drained soils not restricted by bedrock, the total soil C stocks ranged from 11.2 kg C m⁻² in Regosolic soils to 15.9 kg C m⁻² in the self-drained Brunisolic soils, Table 3. The Organic-folisols and the non-

soils are both restricted in depth by bedrock (Table 1). Nevertheless, the Organic-folisols stored 10.3 kg C m⁻² on average. The Podzolic soils had a larger fraction of profile C in mineral soil (about 60 %) compared with other mineral soils. The soils with the lowest proportion of C stock in the mineral soils were the Regosolic (36 %) and the Gleysolic (41 %). Although the self-drained Podzolic and Brunisolic store approximately equal amounts of C in total, there was a significant difference in the proportion stored in the mineral soils with 60 % versus 47 % for the Podzolic and the Brunisolic soils respectively (Table 3).

The N stocks of the mineral soils were in the range of 0.1 to 1.1 kg N m⁻² with water saturated soils showing a tendency for higher N stocks than self-drained soils (Table 4). Additionally, less N was stored in the poorly developed Regosolic soils and Non-soils. The C:N ratios of eluviated and gleyed Brunisolic soils were higher than other mineral soils (Table 4) due to low N concentrations.

The distribution of soil C stock was estimated by soil order and master horizon with typical sub-horizon suffixes in Figure 2. The confidence limits were narrowest for the uppermost horizons and widen downward for all soils types. Particularly the self-drained Brunisolic soils exhibit a large variability in C stocks in the deeper horizons. The largest soil group within the soil database is the self-drained Podzolic. This is also reflected in the narrow confidence limits connected to the C stock estimates of all horizons. Soils with podzolization as the dominating process, here represented by the gleyed Podzolic, self-drained Podzolic and the eluviated dystic Brunisolic soils, showed no significant differences in C stock (6-8 kg C m⁻²) or in thickness of the LFH horizon, Figure 2. The same soil groups were significantly different with respect to C stocks in the Ae horizon (gleyed Podzolic>self-drained Podzolic>eluviated dystic Brunisolic), though there were no significant differences in Ae horizon thickness. The eluviated dystic Brunisols soils were significantly lower in C stocks also in the B horizons, which is also due to a significantly thinner B horizon.

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The self-drained Podzolic and Brunisolic soils differed in C-stock distribution within the profile, even though approximately storing equal amounts of C in total (Table 3). The self-drained Brunisolic stored significantly more in the upper horizons both in the LFH and the A horizon (Figure 2) whereas the Podzolic stored significantly more in the B horizon.

Among the soils influenced by water saturation, but excluding the Organic-wet soils, the Gleysolic had significantly larger C stocks and thicker LFH horizons compared with the gleyed Podzolic and gleyed Brunisolic soils. The C stocks of the LFH horizons of the Gleysolic were the largest of any of the forest floors of the mineral soil; more than 13 kg C m⁻² in average. There are significantly higher C stocks in the B horizon of the gleyed Podzolic than those of the Gleysolic or Brunisolic B horizons.

Uncertainty in soil C stocks by Monte Carlo simulation in 10 profiles

The results from the Monte Carlo simulation for each of the typical profiles sampled from the dataset are given in Table 5. In most cases the simulated C stocks were close to the C stock based on all profiles (Table 3) and the two different coarse-fraction representations used in the simulations gave similar results. The absolute standard error of 1000 simulated SOC stock values within each soil order profile example ranged from 0.1-1.9 kg C m⁻² with 5% relative BD error and increasing to a range of 0.3-6.2 kg C m⁻² for 20% relative BD error. The simulations using mid-class of coarse fraction produced C stocks that were 0.8 to 0.9 kg C m⁻² higher than uniformly distributed stone content for Gleysolic and Brunisolic soils, whereas other estimates showed only little bias, i.e. only slightly higher stock estimates with the mid-class approach.

C and N stocks related to climate

The relationship between soil C stocks of the most frequent soil order, the Podzolic, and the climate parameters, MAP and MAT is illustrated in Figure 3. The Figure shows that both low and high soil C stocks within the soil order can be found in the cold and dry as well as the relatively warm and wet areas of Norway. Despite the large variation, significant positive correlations were found for C and N stocks of Podzolic soils, with both MAT and MAP (Table 6). However, only MAP showed a significant positive correlation with the C and N stock of the Brunisolic-eluviated soils. Among the self-drained Podzolic soils there was a significant and positive correlation between the percentage of C stocks in the mineral soil and MAP. Among the Organic – wet soils, the peats, total C and N stocks were negatively correlated to MAT, Table 6. This coincides with a significantly negative correlation between MAT and peat depth ($r=-0.40$, $p<0.0001$). For the Organic – folisols, the thin organic soils restricted by bedrock, both C and N stocks were significantly and positively correlated with both MAT and MAP. For the other soil groups there were little or no correlation in C and N stocks to any of the climatic variables, Table 6.

C and N stocks related to vegetation

Soils under pine forest show a wide range in soil C stocks and represent the most frequent forest type for both the soils with low C stock and those with high, Figure 4. When excluding the Organic and Non-soils, significant differences in both C and N stocks were found among forests dominated by spruce, pine and deciduous trees. For total C stocks the order was spruce>pine>deciduous while for N stocks pine and deciduous forest switched places. There were also a significant difference in forest floor C:N ratio between the three dominating tree species where pine>spruce>deciduous. Soils under pine forest also had significantly lower C stocks in the mineral soil compartment compared to soils under spruce and deciduous forest. Among the self-drained and gleyed Podzolic soils there was a positive correlation between forest age and each of the variables total C stock, C stored in the forest floor, and C:N ratio and a negative correlation between forest age and the relative amount of

C stored in the mineral soil (Table 7). In the group of self-drained Podzolic soils, increasing forest stand maturity was positively correlated with total C stock, C stock in forest floor and with C:N ratio. For the self-drained Podzolic soils there was a significant negative correlation between the site index and the C stocks in the forest floor and a significant positive correlation between site index and total N stocks and the percentage of C stored in the mineral soil (Table 7). Ground vegetation was registered according to a moisture gradient (dry, medium, wet) and to a nutrient gradient (poor, medium, rich). The moisture gradient was significantly and positively correlated with the total C stocks within a wide range of soils: Organic – wet, Gleysolic, self-drained Podzolic, eluviated and gleyed Brunisolic, and Regosolic soils. The ground vegetation nutrient gradient, however, had a significantly negative correlation to the total C stock of the Gleysolic. The influence of the nutrient gradient on C stock in the mineral soil compartment was more evident, where ground vegetation nutrient level was significantly and positively correlated with the proportion of C stored in the mineral soil compartment of Gleysolic, Podzolic, as well as self-drained Brunisolic soils while there was a significantly and negatively correlated with the C stored in the forest floor (Table 7). The nutrient level was also reflected in the C:N ration of the forest floor showing significantly negative correlations for all soil groups except the Organic and Non-soils.

C and N stocks related to soil depth and water saturation

For all soils, except the Gleysolic and the eluviated and gleyed Brunisolic soils, total C stocks showed significant positive correlations with soil depth. The factor restricting the non-soil and the Organic – folisols is bedrock, while rocks and coarse fraction in addition to bedrock may restrict the soil depth in the other soil groups (Table 8). Ranking soil drainage from excessively well drained (1) to very poorly drained (13) showed that there was a large variation in drainage class also among the shallow Organic – folisols soils giving a significant positive correlation between total C stock and drainage (Table 8). For the soil groups with deep mineral soil, a significant positive correlation between C

stock and drainage was also found, except for the self-drained Brunisolic soils. Depth to groundwater was only registered when this occurred within the depth of the soil profile described. For the self-drained and gleyed Podzolic and the self-drained Brunisolic soils, there was a significant positive correlation between registered depth to groundwater and total C stock (Table 8).

Soil carbon stocks in forested areas of Norway

The total C stock assuming 120 000 km² forest area, was estimated to 1.83 Gt C with confidence limits between 1.71 and 1.95 Gt C. This was achieved after summing the group lsmeans (Table 9) deducting 8% due to skewed mean and assuming a 2 % uncertainty for the total forest area. The estimates for each soil group indicate that 36% of the forest soil C stock are found in the self-drained Podzols. Poorly drained soils with large proportions of C stored in the organic horizons store 40% of the total forest soil C: 20 % in the Organic-wet, 10 % in Gleysols and 10 % in the gleyed Podzolic soils (Table 9). More than 50 % of all soil C in Norwegian forest appear to be stored in soils with podsolization as the dominating soil forming process, including the eluviated Brunisolic soil, self-drained and gleyed Podzolic. The uncertainties in the C stocks for each soil group are connected to the forest area and C stocks estimates and range from 0.9% to 2.4% and are largest for carbon rich soil groups with few observations in the soil database (Table 9).

Discussion

Soil carbon and nitrogen stocks according to soil type

The largest C and N stocks, at the profile level, in the Norwegian forest soil database were found in the Organic-wet soils. These are the Humisols, Mesisols and Fibrisols of the Canadian Organic soil order formed due to excess water and anaerobic conditions. Among the Organic –wet soils 47% belong to the Terric sub-groups, indicating shallow peats with mineral soil layers or bedrock appearing between 60 – 160 cm depth. The large proportion of these shallow peats is probably the

reason why Organic-wet store less C than reported for other Organic or Histosol soils in boreal forests ([De Vos et al. 2015](#); [Tarnocai 1998](#)). The bulk densities used for calculating the C stocks in the organic horizon of the Organic-wet soils are in the range expected in Nordic forested peats ([Laiho et al. 2004](#)) but lower than those given for European forest peats in De Vos et al. ([De Vos et al. 2015](#)).

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Considering the mineral soils, the Canadian soil classification system on order level provides significant differences with regard to C and N stock in the order Gleysolic > Podzolic > Brunisolic > Regosolic soils. Our ranking is consistent with those reported for Canadian forest soils with the exception of the Regosolic soils which in our study have the lowest C stocks (10.8 kg C m^{-2}), while Shaw et al. ([2008](#)) report high stocks (18.5 kg C m^{-2}), i.e. in the same range as the Gleysolic soils. Our explanation for this difference is that a large proportion of the Norwegian Regosolic soils are shallow bedrock-restricted soils, 66% of the Regosolic soils are $\leq 35 \text{ cm}$ deep. The average C stocks for Norwegian soil orders are generally higher than those reported in the Canadian study ([Shaw et al. 2008](#)). The main difference between the two studies is that the Norwegian soils have larger stocks in the organic horizons (LFH- horizons). Studies of Danish forest soils ([Callesen et al. 2015](#); [Vejre et al. 2003](#)) showed that the C stocks of comparable soil units were similar to those found in our study, however, also here our study show larger C and N stocks in the forest floor and lower C stocks in the mineral subsoil. A recent study of boreal and temperate forest soils in 22 european countries (Norway not included) ([De Vos et al. 2015](#)) reported similar C stocks and ranking between comparable soil orders, except for Podzols which have much lower C stocks than found in our study. Podzolization is the dominant soil forming process in Norwegian forest soils; 55 % of the soils in the forest soil database show a podzol morphology reflected in the classification. In addition to the soils in the Podzolic order also the Eluviated Dystric Brunisols of the Brunisolic order have a clear podzol morphology but do not meet the depth or chemical classification criteria for the Podzolic order. The mean C stocks of the Podzolic soils, were higher than those reported from comparable forest soils in

Finland, 5-8 kg C m⁻² down to 1 meter and Sweden 6.5 - 9.5 kg C m⁻² down to 0.5 m ([Liski and Westman 1997](#); [Olsson et al. 2009](#)). Our findings were more in line with Danish and Canadian studies. [Vejre et al. \(2003\)](#) and [Callesen et al. \(2015\)](#) reported C stocks for Danish forest Podzols down to 100 cm and including forest floor of 14.6 and 16.9 kg C m⁻² respectively. [Shaw et al. \(2008\)](#) and [Tarnocai \(1998\)](#) reported C stocks of 15.6 and 19.3 kg C m⁻² respectively for Canadian boreal forests Podzolic soils. Some of the discrepancies between the estimates of Podzol C stocks particularly for the Nordic countries may be due to differences between classification system and identification criteria for Podzols ([Agriculture Canada Expert Committee on Soil Survey 1987](#); [FAO Unesco 1990](#); [Soil Survey Staff 1999](#); [WRB 2015](#)). The weakly developed soils with podzol morphology, the Eluviated Dystric Brunisols in our study have a total C stock of 11.2 kg C m⁻² down to 50 cm and a C stock in the mineral soil down to 50 cm of 4.2 kg C m⁻² which is more in accordance with the Swedish Podzols ([Olsson et al. 2009](#)).

The Organic-folisols and non-soil (soil depth < 10 cm) are the soil groups with lowest C stocks. There are few studies that report C stock from such soils in forested areas. However, particularly the Organic-folisols store considerable amounts of C and represent a soil type frequently occurring in Norway in the transition between forest and heath and moorland areas. The C stocks of the Organic-folisols are within the range suggested for organic rich Leptosols in moorlands of Scotland ([Stutter et al. 2009](#)) and Northern England ([Tipping et al. 2007](#)) as well as for Norwegian heathland areas ([Strand et al. 2008](#)).

The main reason for the higher C stocks in organic horizons of Norwegian forest soils appears to be greater horizon thickness and higher bulk densities. Compared with organic horizon thicknesses reported from other Nordic countries ([Liski and Westman 1995](#); [Vejre et al. 2003](#)), Norwegian organic surface horizons are thicker. However, O horizons of Podzols investigated by [Olsson et al. \(2009\)](#) had

an average thickness of 8.2 cm, thus similar to the average for the organic horizons of the Podzolic soils in this study which was 9.6 cm. The bulk density data we used for calculating the C stocks of the organic horizons were collected from various sources and although all were from Norwegian forest soils they are not necessarily representative for those of the forest soil database. Standard core sampling were used to determine these bulk densities and compression of the organic soil may have introduced artificially high bulk densities. However, the median bulk density values used for our calculations were 110-171 kg m⁻³, which is well within the range reported for similar horizons e.g. (De Vos et al. 2015). For norwegian forests, the average bulk density was 165 kg m⁻³ for the organic horizon above mineral soils were similar to the bulk densities of the more decomposed OH horizons and hydromorphic or semi-terrestrial organic horizon reported by De Vos et al. (2015). The C concentration in the organic horizons, mean 39.5 % with 95% confidence limits between 38.8 and 40.3 is similar to the range reported in other studies eg (De Vos et al. 2015; Olsson et al. 2009; Vejre et al. 2003).

Our error estimates using the standard error on profile soil C stock estimates based on uncertainties in bulk density, coarse fraction and C content for a representative set of soil profiles (Table 5) indicate that the largest errors are found in the Organic (1.9 – 6.2 kg C m⁻²), Gleysolic (1.1-3.7 kg C m⁻²) and gleyed soils (1.0 – 3.7 kg C m⁻²), less for the self-drained mineral soils (0.7 -3.2 kg C m⁻²). These errors are not large enough to explain the differences between C stocks in our study and those of other comparable studies.

C and N stocks related to climate

Relationships between soil C stock and MAT and MAP were not obvious, evidently other more site specific parameters have a larger influence on the soil C stocks. Even though they were calculated

for each forest inventory plot, correcting for altitude, MAT and MAP are still macro-climatic parameters that do not necessarily reflect the local climate or seasonal variations important for soil C accumulation. Norway has a highly variable topography which modifies the local climate. Interaction between temperature and topography was also pointed out by Johnson et al. (2011) as being of major importance for controlling soil C stock in high-latitude systems. However, for the Podzolic soils there were a significant positive correlations between both C and N stock and MAT and MAP (Figure 3, Table 6). For the self-drained Podzolic soil, MAP was also positively correlated with the proportion of C in the mineral soil compartment. However, this was not the case for the wetter gleyed Podzolic where the increase in soil C stock was mostly connected to the organic horizon. This is in accordance with Olsson et al. (2009) study of Swedish Podzols. Callesen et al. (2003) and De Vos et al. (2015) also found that both MAT and MAP were important for total forest soil C stock, but that MAP was of relative greater importance than MAT for mineral soil C stocks. Warm and humid environments enhances forest productivity increasing both litter production and decomposition (Van Cleve and Powers 1995), while a precipitation surplus will transport organic compounds downwards in the soil profile where it may be illuviated and stabilized in the mineral soil, processes characteristic of podzolization e.g. (Lundstrom et al. 2000). Periodic water saturation and fluctuating ground water table as found in the gleyic Podzolic may obscure these transport, sorption and stabilization processes. The negative correlations between C:N ratios of the forest floor and MAP and MAT for the self-drained Podzolic, Table 6, correspond to the findings of Callesen et al. (2007) for forest floor of Nordic well drained forest soils. This negative correlation with MAT and MAP could either be ascribed to the initial litter quality determined by forest and ground vegetation, or to increased humification, or the ecosystem N status being more favourable in areas with higher MAT and MAP. Olsson et al. (Olsson et al. 2009) found that of all site factors investigated N deposition showed the strongest positive correlation with soil C stocks for Swedish Podzols. In Norway areas that receive the higher N deposition coincide with the areas that receive the highest precipitation

535 ([Sft 2006](#)) and MAP and MAT are positively correlated ($r=0.69$, $p<0.0001$) making it difficult to
536 separate these effects.

537

538 For the Organic –wet soils there was a significantly negative correlation between the C and N stock
539 and MAT and length of growing season but no correlation with MAP (Table 6). The fact that there
540 was a significant negative correlation between the profile depths of the Organic-wet soils and MAT
541 ($r=-0.39$, $p<0.0001$) could explain the negative correlation between C and N stocks and MAT. Most of
542 the forested Organic soils were drained at some point as a forest management practice to promote
543 forest productivity. Lowering of the ground water table gives better aeration accelerating the
544 decomposition more in warmer parts of the country than in colder. As many of the Organic-wet soils
545 are in the Terric subgroup, a loss of C due to decomposition would be more evident than in deeper
546 peat soil. The lack of correlation with MAP shows that the peat formation in these forested areas
547 probably is more due to topographically impeded drainage than to precipitation surplus. Contrary to
548 the Organic-wet soils the C and N stocks of the Organic-folisols were positively correlated to both
549 MAT and MAP, Table 6, suggesting that the C and N stocks are more related to vegetation and
550 productivity.

551

552 C and N stock related to vegetation

553 There were no differences between soil C stocks under Pine and Spruce dominated forests, however
554 significantly less C was found in soils under deciduous forest (Figure 4). This could be ascribed to
555 spruce being the dominating tree species in productive forests while deciduous forest dominates in
556 less productive forest ([Granhuis et al. 2012](#)). Alternatively the lower soil C stocks in forest dominated
557 by deciduous tree species could be explained by a more rapid C turnover as suggested by Melvin et
558 al. ([2015](#)) after comparing soil C stock in Black spruce and Paper birch dominated boreal forest in

Alaska. Spruce-dominated forest have a larger proportion of the C stock in the mineral soil, suggesting that more soil C is stabilized by minerals. Pine differed from spruce dominated forest by being represented more frequently on soils with both low and high C stock (Figure 4). Pine appears to adapt more to adverse growing conditions ranging from the poorly drained Organic - wet to the excessively well drained Organic – Folisols and Non-soils. Pine-dominated forest also has a larger proportion of the C stock in the forest floor suggesting that disturbances, such as site preparation and drainage, probably would cause significant C loss. De Vos et al. (2015) found that humus forms and tree species were the most useful predictors for C stocks in the forest floor. Our results confirm this for the dominating tree species in Norwegian forests. For the N stock the differences was not reflected in the forest floor but in the mineral soil compartment.

Forest stand age and forest stand maturity class reflect the rotation length between harvests. Several studies have suggested that an increase in rotation length would increase the C stocks in the forest system e.g. (de Wit and Kvindesland 1999; Jandl et al. 2007). Only the self-drained Podzolic soils showed any significant positive correlation between forest stand age, forest maturity class, and total soil C stocks as such. However both the self-drained and the gleyed Podzolic soils showed a significantly positive correlation between forest stand age and the C stocks of the forest floor and a significantly negative correlation between forest stand age and the proportion of C stored in the mineral soil (Table 7). This suggest that increasing the rotation length only increase the more labile C stock in the forest floor and does not contribute to any increase of more stable C stock in the mineral soil horizons. For Swedish Podzols Olsson et al. (2009) found no significant correlation between site index (equivalent to site capacity in their paper) and total soil C stocks, but contrary to our study they found a positive correlation between site index and the C stocks of the O horizon. As stated by Olsson et al. (2009) the relationship between site index and C stocks is complex. The more fertile sites may have a more rapid turnover suggesting lower C stock, a greater translocation of C to

deeper soil horizon, more fine roots in deeper mineral soil horizons which fits with our observations. However higher productivity also gives larger inputs of litter. The denser forest stands are often found in high site index, which, through blocking sunlight and intercepting rainfall in the dense canopy may induce colder and dryer soil conditions adverse to decomposition, thereby promoting higher C stocks in the forest floor. However, no support for this was found in our study.

We found that ground vegetation classified according to moisture were good indicators of C and N stocks particularly for the forest floor. While the ground vegetation nutrient classes were better indicators of the proportion of C in the mineral soil horizon. Combining ground vegetation moisture and nutrient classes should give a good indication of the total soil C stock. Particularly for the moist vegetation types, periodic anaerobic conditions restricting the decomposition might conserve the properties of the ground vegetation litter and thereby lead to a closer and more evident correlation with the current ground vegetation. Moist vegetation types often have sphagnum moss cover preventing evapotranspiration, lowering soil temperature and thus reducing decomposition. Moss vegetation may play a key role in C dynamics particularly in Boreal ecosystems ([Turetsky et al. 2012](#)).

C and N stocks related to soil depth and water saturation

We found that soil C stocks increase with more poorly drained soils, this goes for all soil types but for the soil groups where drainage is part of the classification criteria this relationship was not always evident (Table 8). The soils classified as Gleysolic or as gleyic great groups or sub groups of other orders store nearly 4 kg C m⁻² more C than the self-drained soils (Table 3, Figure 2). Virtually all of this was due to larger stocks in the organic surface horizon. Other studies have also shown that poor drainage results in higher C stocks particularly in the organic horizon e.g. ([Tan et al. 2004](#)). Organic matter in these horizons has little or no interaction with mineral soil material, the main stabilizing

factor being water-saturation. Draining these poorly drained soils will probably cause an increase in loss of C due to accelerated decomposition which may or may not be compensated by increased productivity (Jandl et al. 2007). We also found a clear correlation between C stocks and drainage classes in the self-drained soils. Olsson et al. (2009) also found an increase in C stock from dry to fresh to moist sites for Swedish forest Podzols and that this increase was exclusively related to differences in the C stocks of the O-horizon. They suggest several possible explanations for this ranging from reduced decomposition due to periodic water saturation, high production of litter, differences in litter quality and differences in distribution of root litter. Kleja et al. (2008) found more fine root litter in the O horizons and less fine roots in the mineral soils of moist Podzols compared to dry Podzols.

The Norwegian Organic-folisols are shallow soils lying directly on bedrock. These soils are extremely exposed to changing seasonal weather conditions. The bedrock micro-topography providing pockets for accumulation of particles and water as well as erosion areas experiencing extreme drought. The rapidly changing moisture conditions influence decomposition processes, plant growth and litter production and thereby accumulation of soil C, however, forest management practices will have minor effect on the C stocks in these soils.

Total carbon stock in forested areas in Norway

The estimates for the mean total C stocks in Norwegian forest soil 1.83 (1.71 – 1.95)Gt C is larger than the 1.6 Gt C previously published in Kjonaas et al. (2000) for a comparable forest area. Kjonaas and co-workers used data from the same database as us but only differentiated between organic and mineral soils. In the present study we calculated the total forest soil C stock by summing the total C stock of different soil groups assuming that their presence in the soil database is

632 representative for area covered by soil groups in Norwegian forest. This may introduce additional
633 uncertainties but will hopefully provide useful information to government agencies seeking best
634 management practice for forestry with regard to forest soil C sequestration. A substantial part (40 %)
635 of the Norwegian forest soil C is found in poorly drained soils that may all be particularly sensitive to
636 environmental change and management.

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641 **Conclusion**

642 Carbon and N stocks in Norwegian forest soils of different taxonomic classes vary from 10.8 kg C m⁻²
643 and 0.43 kg N m⁻² for the Regosolic soils to 31.3 kg C m⁻² and 1.10 kg N m⁻² for the Organic-wet soils.
644 Shallow soils (< 30 cm) restricted by bedrock may store between 2 and 10 kg C m⁻². Assuming a
645 forest area in Norway of 120 000 km² and that the forest soil database is representative for the
646 Norwegian forest, the total forest soil C stocks for Norway was estimated to 1.83 Gt C with CL95%
647 1.71 – 1.95 Gt C. The self-drained Podzolic and Brunisolic soils cover approximately 52 % of the
648 forested area and we estimate that they may store 48% of the total forest soil C stocks. For the
649 Podzolic soils there were a positive relationship between total C stocks, temperature and
650 precipitation. Mean annual precipitation was particularly important for the C stored in the mineral
651 soil. Poorly drained soil types cover approximately 32 % of the forest area and we estimate that they
652 may store approximately 47 % of the total forest soil C. The C stocks in the forest floor were
653 generally high compared with estimates from other studies of boreal forests, and largest in soils with
654 periodic or permanent water-saturation. There was no significant difference between total soil C
655 stocks under spruce and pine forest but these store more than soils under deciduous forest,
656 probably reflecting that deciduous tree species were more common in low productive forest. Soils
657 under pine forest had larger C stocks in the forest floor and was more frequently occurring on wet
658 and peaty soils. For spruce forest more of the soil C stock was found in the mineral soil
659 compartment. This suggests that the C stocks under pine forest may be most sensitive to
660 management and changes in environment.

661

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Table 1: Soils of the Norwegian forest soil database grouped according to the dominating process influencing C stocks and Canadian soil classification and World Reference Base (WRB) reference soil group equivalents.

Stratification of soils used in this study	Dominating process	Canadian soil classification [‡]				Equivalent WRB
		Order	Great group	N	Sub groups	
Non soils [‡]	Drought-root restriction, soil <10 cm	Non-soil		28		Leptosol
Gleysolic	Water saturation	Gleysolic	Gleysol	61	Orthic, Rego, Fero	Gleysol
			Humic	34	Orthic, Rego	Podzol
Podzolic – self drained	Podzolization	Podzolic	Ferro-Humic	75	Orthic, Sombric, Orthstein	Podzol
			Humo-Ferric	307	Orthic, Sombric, Orthstein	Podzol
			Humic	9	Orthic	Podzol
Podzolic - gleyed	Podzolization/water saturation		Ferro-Humic	16	Gleyed, Gleyed Sombric, Gleyed Orthstein	Podzol
			Humo-Ferric	79	Gleyed, Gleyed Sombric, Gleyed Orthstein	Podzol
Brunisolic – self drained	Brunification	Brunisolic	Dystric	27	Orthic, Duric,	Cambisol
			Eutric	5	Orthic	Cambisol
			Melanic	2	Orthic	Cambisol
			Sombric	25	Orthic	Cambisol
Brunisolic - eluviated	Podzolization		Dystric	76	Eluviated	Arenosol
			Sombric	4	Eluviated	Cambisol
Brunisolic - gleyed	Water saturation/brunification/ podzolization		Dystric	33	Gleyed Eluviated, Gleyed,	Cambisol
			Eutric	1	Gleyed Eluviated	Cambisol
			Sombric	6	Gleyed, Gleyed Eluviated	Cambisol
Regosolic	Drought/water saturation/ root restriction/shallow soils	Regosolic	Humic	29	Orthic, Gleyed	Rego-/Fluvi-/Leptosol
			Regosol	66	Orthic, Gleyed	Rego-/Fluvi-/Leptosol
Organic – folisols	Drought – root restriction/shallow soils	Organic	Folisol	51	Hemic, Humic, Histic	Histosol
Organic - wet	Water saturation		Fibrisol	13	Typic, Terric, Mesic, Humic	Histosol
			Mesisol	30	Terric, Typic, Humic	Histosol
			Hemisol	63	Terric, Typic, Fibric	Histosol

[‡] The distribution of soil profiles is given on Great group level and the Subgroups for each great group are listed ranked according to the most frequently occurring. [†] Reference Soil Group.

[‡] Non-soils are soils less than 10 cm deep

Table 2. Classification, horizon designations, profile depths, carbon and nitrogen stocks, and C/N ratio of the forest floor of the ten soil individual profiles picked out from the Norwegian forest soil database for the Monte Carlo simulation of uncertainties.

Profile representative of	Canadian soil classification	Horizons†	Profile depth (cm)	Organic horizons (cm)	C stock C kg m ⁻²	N stock N kg m ⁻²	C/N ratio in forest floor
Non-soils <10 cm	Non soil	LFH, R	8	8	1.40	0.05	
Gleysolic	Orthic Humic Gleysol	LFH, Ah, Bg, Cgj	75	9	17.84	0.99	22
Podzolic - self-drained	Orthic Humoferric Podzol	LFH, Ae, Bf1, Bf2, BC	58	8	15.14	0.60	28
Podzolic - gleyed	Gleyed Humoferric Podzol	LFH, Ae, Bf, Cgj, Cg	85	12	18.48	0.92	34
Brunisolic - self-drained	Orthic Sombric Brunisol	LFH, Ah, Bm, C	42	9	13.42	0.52	31
Brunisolic - eluviated	Eluviated Dystric Brunisol	LFH, Ae, Bf, BC, C	90	6	12.10	0.27	40
Brunisolic - gleyed	Gleyed Dystric Brunisol	LFH, Ahej, Bf, BC, Cgj	70	10	15.52	0.53	38
Regosolic	Orthic Regosol	LFH, Ae, R	32	17	10.77	0.42	27
Organic – folisols	Hemic Folisol	LFH, R	13	13	8.81	0.26	34
Organic - wet	Terric Humisol	Of1, Of2, Oh, Om, C	70	65	30.42	0.70	

† Description of the horizon designations: The organic horizons(>17% organic C): L- litter, F – fragmented partly decomposed, H- humified, well decomposed , O –peat of either, f-fibric, m-mesic or h – humic material. The mineral soil A, B, C, horizons with suffices h -organic matter enrichment, e -eluviation, f -enrichment with amorphous material: organic matter, Al and Fe, g-gleyed, m-weathered, j-modifier of weak and inadequate expression of a suffix, The R – indicates bedrock.

Table 3 Total C stocks and percentage of C stocks in mineral soil grouped according to Canadian soil orders and soil water related properties. Lower case letters show significant ($\alpha=0.05$) differences between the soil groups tested.

			C stock kg C m ⁻²				% C in mineral soil					
			N	%	mean	median	ICL†	uCL†	mean	median	ICL†	uCL†
Non-soils			28	3	1.62e	1.4	-1.8	5.0	-	-	-	-
Gleysolic			95	9	19.33b	17.8	17.5	21.2	41cd	34	36	46
Podzolic	- self-drained	391	38	15.46bc	14.1	14.6	16.4	60a	63	58	62	
	- gleyed	95	9	18.41b	18.3	16.6	20.3	61a	64	57	66	
Brunisolic	- self-drained	59	6	15.87bc	13.4	13.5	18.2	46bcd	52	40	52	
	- eluviated	80	8	12.06cd	10.8	10.0	14.1	47bc	48	42	52	
	- gleyed	40	4	14.12cd	12.7	11.3	17.0	52b	49	45	59	
Regosolic			95	9	11.11d	9.5	9.3	13.0	36d	33	32	41
Organic	- folisols	51	5	10.26d	8.8	7.7	12.8	-	-	-	-	
	- wet	106	10	31.32a	30.5	29.6	33.1	-	-	-	-	

† ICL lower confidence limit, uCL upper confidence limit, given as 95% of the least significant mean.

Table 4 Nitrogen stocks and C:N ratio in forest floor grouped according to Canadian soil orders and soil water related properties. Lower case letters show significant ($\alpha \sim 0.05$) differences between the soil groups tested.

		N stock kg N m ⁻²				C:N ratio forest floor				
		N	mean	median	ICL†	uCL†	mean	median	ICL†	uCL†
Non-soils		28	0.06h	0.04	-0.08	0.20	-	-	-	-
Gleysolic		95	0.78b	0.71	0.71	0.86	29c	26	27	30
Podzolic	- self-drained	391	0.59cde	0.51	0.54	0.62	30c	29	29	31
	- gleyed	95	0.70bc	0.64	0.62	0.77	30c	29	28	31
Brunisolic	- self-drained	59	0.65bcd	0.57	0.55	0.75	28c	27	26	30
	- eluviated	80	0.41fg	0.38	0.32	0.49	36a	35	34	38
	- gleyed	40	0.51def	0.40	0.40	0.63	33b	36	30	36
Regosolic		95	0.43efg	0.34	0.36	0.51	29c	28	27	31
Organic	- folisols	51	0.34g	0.28	0.23	0.44	-	-	-	-
	- wet	106	1.10a	1.00	1.03	1.17	-	-	-	-

†ICL lower confidence limit, uCL upper confidence limit, given as 95% of the least significant mean.

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Table 5 The Monte Carlo simulation based on typical soil profiles according to Canadian soil classification (orders and selected subgroup), standard deviation for each simulation are written in brackets.

C stocks (kg C m ⁻²) from Mont Carlo simulation†							
		CF uniform distribution			CF mid-class from field		
		BD5	BD10	BD20	BD5	BD10	BD20
Non-soils		1.4(0.1)	1.4(0.2)	1.4(0.3)	1.4(0.1)	1.4(0.2)	1.4(0.3)
Gleysolic		17.8(1.6)	17.8(2.2)	17.8(3.8)	18.6(1.1)	18.6(1.9)	18.6(3.7)
Podzolic	- self-drained	15.1(1.2)	15.1(1.8)	15.1(3.2)	15.4(0.9)	15.4(1.6)	15.4(3.1)
	- gleyed	18.5(1.3)	18.5(2.1)	18.5(3.8)	18.5(1.1)	18.5(2.0)	18.5(3.7)
Brunisolic	- self-drained	13.4(1.1)	13.4(1.7)	13.4(2.9)	14.3(0.8)	14.3(1.5)	14.3(2.9)
	- eluviated	12.1(1.0)	12.1(1.4)	12.1(2.4)	12.3(0.8)	12.3(1.3)	12.2(2.4)
	- gleyed	15.5(1.3)	15.5(1.9)	15.5(3.2)	16.0(1.0)	16.0(1.7)	16.0(3.2)
Regosolic		10.8(0.7)	10.8(1.2)	10.8(2.2)	10.8(0.7)	10.8(1.2)	10.8(2.2)
Organic	- folisols	8.8(0.6)	8.8(1.0)	8.8(1.8)	8.8(0.6)	8.8(1.0)	8.8(1.8)
	- wet	30.4(1.9)	30.4(3.0)	30.5(6.2)	30.4(1.9)	30.4(3.3)	30.5(6.2)

†The Monte Carlo simulations were run on combinations of three different error estimates for bulk density (BD) 5, 10 or 20% (BD5, BD10 and BD20) and coarse fraction (CF) estimates based on either a uniform distribution or the mid-class from field registration.

Table 6. Relationships between some climate parameters and total C and N stocks, C stocks and C:N ratios of the forest floor, and the proportion of C stock stored in the mineral soil compartment for the different Norwegian forest soil types. Only statistical significant ($p<0.05$) spearman correlation coefficients are listed in the table.

		Non-soils	Organic-follisols	Organic - wet	Gleysolic	Podzolic, self-drained	Podzolic-gleyed	Brunisolic self- drained	Brunisolic - eluviated	Brunisolic - gleyed	Regosolic
MAT (C°)	Tot-C (kg C m ⁻²)		0.28*	-0.36***	0.20*	0.32***	0.57***				
	Tot-N (kg N m ⁻²)		0.36**	-0.38***		0.34***	0.49***				
	C-forest floor (kg C m ⁻²)					0.20***	0.31**				
	C:N ratio forest floor					-0.24***				-0.37*	
	C % in mineral soil										
MAP (mm)	Tot-C (kg C m ⁻²)		0.29*			0.28***	0.43***		0.25 *		
	Tot-N (kg N m ⁻²)		0.46***			0.32***	0.30**		0.25*		
	C-forest floor (kg C m ⁻²)					0.12*	0.35***				
	C:N ratio forest floor					-0.33***			-0.33***		
	C % in mineral soil					0.14**					
Growing season (Σ days >5°C)	Tot-C (kg C m ⁻²)			-0.30**		0.26***	0.42***				
	Tot-N (kg N m ⁻²)		0.34*	-0.31**		0.29***	0.35**				
	C-forest floor (kg C m ⁻²)		0.35*			0.20***					
	C:N ratio forest floor					-0.12*					
	C % in mineral soil										
Altitude (m above sea level)	Tot-C (kg C m ⁻²)			0.21*		-0.12*					
	Tot-N (kg N m ⁻²)										
	C-forest floor (kg C m ⁻²)					-0.12*					
	C:N ratio forest floor					0.12*				0.37*	
	C % in mineral soil				-0.25*						-0.23*

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 7. Relationships between some forest and vegetation parameters and total C and N stocks, C stocks and C:N ratios of the forest floor, and the proportion of C stock stored in the mineral soil compartment for the different Norwegian forest soil types. Only statistical significant ($p < 0.05$) spearman correlation coefficients are listed in the table.

		Non-soils	Organic-folisols	Organic - wet	Gleysolic	Podzolic, self-drained	Podzolic-gleyed	Brunisolic self-drained	Brunisolic - eluviated	Brunisolic - gleyed	Regosolic
Forest age (y)	Tot-C (kg C m^{-2})					0.16**					
	Tot-N (kg N m^{-2})										-0.37**
	C-forest floor (kg C m^{-2})					0.25***	0.45***				
	C:N ratio forest floor					0.30***	0.41**				0.40**
	C % in mineral soil					-0.15*	-0.38**				
Ground vegetation, Moisture (1=dry- 3=moist)	Tot-C (kg C m^{-2})			0.24*	0.55***	0.15**			0.39***	0.40**	0.45***
	Tot-N (kg N m^{-2})				0.52***	0.17***			0.48***	0.34*	0.43***
	C-forest floor (kg C m^{-2})				0.42***	0.11*			0.32**		0.38***
	C:N ratio forest floor				-0.21*	-0.22***			-0.35**		
	C % in mineral soil										
Ground vegetation Nutrient (1= poor – 3=rich)	Tot-C (kg C m^{-2})		0.35*		-0.24*				0.23*	0.45**	0.29**
	Tot-N (kg N m^{-2})									-0.34*	
	C-forest floor (kg C m^{-2})				-0.39***	-0.36***	-0.49***	-0.35**			
	C:N ratio forest floor				-0.50***	-0.53***	-0.52***	-0.56***	-0.39***	-0.66***	-0.48***
	C % in mineral soil				0.46***	0.42***	0.47***	0.44***	0.25*		
Forest stand maturity (1= young – 5=mature)	Tot-C (kg C m^{-2})					0.15**					
	Tot-N (kg N m^{-2})										-0.25*
	C-forest floor (kg C m^{-2})					0.15*					
	C:N ratio forest floor					0.17**					
	C % in mineral soil						-0.28*				
Site index (6-26)	Tot-C (kg C m^{-2})					0.21***	0.25*				0.31*
	Tot-N (kg N m^{-2})					-0.27***					
	C-forest floor (kg C m^{-2})										
	C:N ratio forest floor				-0.31*	-0.44***		-0.31*			-0.37**
	C % in mineral soil				0.35*	0.28***	0.28*	0.33*			

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8. Relationships between some hydrology and drainage related parameters with regard to total C and N stocks, C stocks and C:N ratios of the forest floor, and the proportion of C stock stored in the mineral soil compartment for the different Norwegian forest soil types. Only statistical significant ($p<0.05$) spearman correlation coefficients are listed in the table

		Non-soils	Organic-folisols	Organic - wet	Gleysolic	Podzolic, self-drained	Podzolic-gleyed	Brunisolic self- drained	Brunisolic - eluviated	Brunisolic - gleyed	Regosolic
Soils depth (cm)	Tot-C (kg C m^{-2})	0.66***	0.68***	0.77***		0.16***	0.22*	0.42**			0.47***
	Tot-N (kg N m^{-2})	0.73***	0.75***	0.69***	0.23*	0.19***	0.31**	0.47***			0.54***
	C-forest floor (kg C m^{-2})	0.70***	0.63***								
	C:N ratio forest floor				-0.21*				0.28*		
	C % in mineral soil				0.33**	0.16**	0.36***				
Drainage (1=excessively well – 13 =very poor)	Tot-C (kg C m^{-2})		0.49***	0.21*	0.30**	0.18***	0.27**		0.49***	0.36*	0.31**
	Tot-N (kg N m^{-2})		0.50***	0.23*	0.28**	0.17***	0.25*		0.43***	0.57***	0.33***
	C-forest floor (kg C m^{-2})		0.38*		0.39***		0.22*	0.30*	0.40***		0.33**
	C:N ratio forest floor								-0.28*	-0.36*	
	C % in mineral soil				-0.38***						
Depth to ground water (cm)	Tot-C (kg C m^{-2})					0.28***	0.25*	0.48**			
	Tot-N (kg N m^{-2})					0.27***					
	C-forest floor (kg C m^{-2})								0.32*		
	C:N ratio forest floor										
	C % in mineral soil										

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

Table 9. Estimates of the total C stock and uncertainty given as gigaton (Gt C) in Norwegian forest soils based on Ismean C stock and corresponding area for soil types present in the Norwegian soil forest database.

							Gt C			
		% of soils	Area km ²	CV _{Area} †	CV _{SOC} ‡	CV _{Total} §	SD tot	C in soil	ICL	uCl
Non-soils	< 10cm	3	3600	16.7%	2.4%	16.9%	0.0010	0.006	0.004	0.008
Gleysolic		9	10800	9.9%	1.2%	10.0%	0.0208	0.208	0.168	0.249
Podzolic	- self-drained	38	45600	4.0%	0.6%	4.0%	0.0283	0.707	0.652	0.762
	- gleyed	9	10800	9.9%	1.2%	10.0%	0.0199	0.199	0.160	0.237
Brunisolic	- self-drained	6	7200	12.0%	1.4%	12.0%	0.0138	0.114	0.088	0.141
	- eluviated	8	9600	10.3%	1.3%	10.4%	0.0121	0.116	0.093	0.140
	- gleyed	4	4800	14.9%	2.1%	15.1%	0.0103	0.068	0.048	0.088
Regosolic		9	10800	9.9%	1.1%	10.0%	0.0121	0.121	0.097	0.145
Organic	- folisols	5	6000	13.4%	1.4%	13.5%	0.0083	0.062	0.046	0.078
	- wet	10	12000	9.4%	0.9%	9.4%	0.0367	0.389	0.317	0.460

† Coefficient of variances connected to the area covered by the soil type, ‡ Coefficient of variances connected to the mean C stocks of the soil type, § The combined CV based on the CV_{area} and CV_{soc}, ICL and uCL are the lower and upper 95 % confidence limit

Figure captions:

Figure 1. Map of Norway showing forested areas and the grid plots where the forest soils were described and sampled.

Figure 2. Carbon stock distribution by master horizon and dominant soil classification. Error bars confidence limit, given as 95% of the least significant mean for the horizon thickness and C stocks. The full line indicates the mineral soil surface; the dotted line indicates the average depth of the soil profiles.

Figure 3. Total carbon stocks of 488 in Norwegian Podzolic forest soils plotted against mean annual precipitation (mm) and mean annual air temperature (C°).

Figure 4. Number of soil profiles under either deciduous, pine or spruce dominated forest grouped according to intervals of soil C stock given in kg C m⁻².

Draft

Map of Norway showing forested areas and the grid plots where the forest soils were described and sampled.

828x1173mm (72 x 72 DPI)

Carbon stock distribution by master horizon and dominant soil classification. Error bars confidence limit, given as 95% of the least significant mean for the horizon thickness and C stocks. The full line indicates the mineral soil surface; the dotted line indicates the average depth of the soil profiles

Total carbon stocks of 488 in Norwegian Podzolic forest soils plotted against mean annual precipitation (mm) and mean annual air temperature (C°).
97x206mm (299 x 299 DPI)

Number of soil profiles under either deciduous, pine or spruce dominated forest grouped according to intervals of soil C stock given in kg C m⁻².
130x111mm (300 x 300 DPI)