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Lime availability in soil, humus, and water.

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Lime availability in soil, humus, and water

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Summary:

Calcium (herein a proxy for lime) is an important nutrient for plants and its availability within an area can favour the occurrence and/or dominance of certain plant species. Regional and local scale studies were carried out in the northern Trøndelag county to assess calcium availability in different media (soil, humus, and water) and within areas located below and above the marine limit. This study used stream water (only regional), humus, and mineral soil data to quantify the availability of calcium. These datasets were combined with the previously defined calcium availability index for bedrock units to elaborate an integrated calcium availability map using Fuzzy Logic and Index Overlay approaches.

Calcium availability in soil and humus from areas below and above the marine limit are undistinguishable. The stream water samples located below the marine limit are slightly enriched in calcium relative to those taken above, but this is likely due to contamination derived from nearby farming. Notably, the spatial correlation between calcium in humus and bedrock is greater than that of calcium in soil and bedrock regardless of the survey scale. This suggests that for some elements, humus may be a better media to characterize the underlying lithologies, which may have important implications for mineral exploration surveys and environmental assessments. Our methodology is validated by the fact that in both surveys (regional and local), lime-rich forest types were mainly contained in areas having intermediate to high calcium availability values in different media and the integrated calcium availability map. Despite its limitations, the methodology described in this study provides a first order tool to identify forest types that commonly occur in areas with low and high calcium availability.

Keywords:	Lime availability	Geochemistry
Fuzzy logic	Ecological mapping	Forest types

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1. Introduction

Lime is an important source of calcium, an essential nutrient for plants that reduces soil acidity and can determine the occurrence and/or dominance of certain plant species (and associated ecosystems) in an area (**e.g., White and Broadley, 2003**). Therefore, quantifying lime availability in natural sources such as bedrock, debris (soil and humus) and water can be useful for predicting and/or characterizing the biodiversity of areas for which in-situ observations of natural species are limited or non-existent. The term "lime" refers to inorganic Ca-rich compounds (e.g., $CaCO_3$), and thus, analytical calcium from different media can be used as a proxy to quantify lime availability.

The main objectives of this project are: i) describe mechanisms related to lime content (herein calcium content), ii) identify relevant datasets and develop methods for compiling national datasets for lime availability (herein calcium availability) in debris and water, and iv) evaluate data types/sets that can be used, and test against areas having empirical natural species observations.

This study focuses on characterizing calcium availability in areas above and below the marine limit, and it emphasizes the development of a national scale methodology that combines various media layers (soil, humus, stream water and bedrock) into regional- and local-scale integrated calcium availability maps (ICA). Finally, ICAs were spatially correlated with in-situ forest type observations to evaluate the reach and limitations of the proposed methodology.

2. Area of study

The northern portion of Trøndelag county (formerly Nord-Trøndelag) was selected for this study (**Fig. 1**). This area comprises a large diversity of geological units, including (meta-) extrusive and intrusive felsic to ultramafic rocks as well as silica (e.g., sandstone/quartzite) and carbonate-rich (e.g., limestone/marble) (meta-) sedimentary rocks (**Geological Survey of Norway, 2021**). Moreover, northern Trøndelag is covered by multiple geochemical surveys that include soil, humus, stream water and bedrock.

Regional and local scale approaches were taken to characterize calcium availability in this area. The regional approach corresponds with a compilation of major and trace element datasets for soil (**Reimann et al. 2015**), humus (**Finne and Eggen, 2015; Reimann et al. 2015**), and stream water (**Ryghaug et al. 1994; Banks et al.,2001**), and a map of calcium availability in bedrock (**Heldal and Torgersen, 2020**) (**Fig. 2**). The local scale study consisted of a mineral soil and humus geochemical survey done at the Steinkjer municipality (**Fig. 3**). This local survey was designed to improve the characterization of sources of calcium found both below and above the marine limit, as the sources below the marine limit are often under-represented in regional datasets.

The marine limit is defined as the highest level that the sea reached after the last glaciation and represents the highest possible level (above the present sea level) at which marine sediments can be found. The under-representation of areas below the marine limit in geochemical surveys responds to: 1) majority of sediments currently inland were deposited above the marine limit, 2) areas below the marine limit are commonly covered by farmland, increasing the possibility of sample contamination due to agricultural activities, and 3) the representativity of the underlying bedrock is limited in areas below the marine limit as these are often covered by fluvial, fluvioglacial and beach/fjord sediments (highly transported sediments).

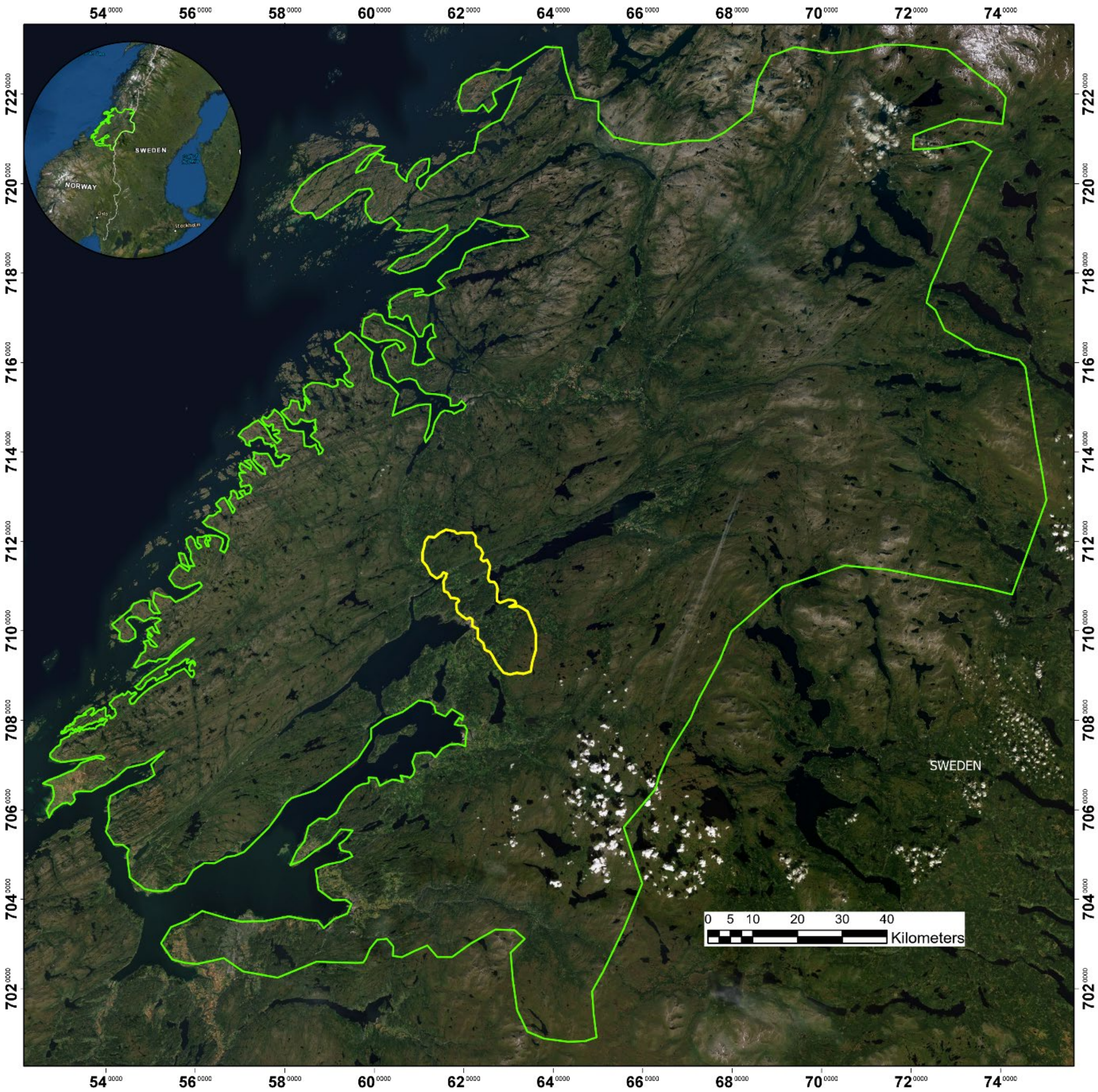

Figure 1. Northern Trøndelag. Green and yellow correspond to areas covered by the regional and local (Steinkjer) surveys

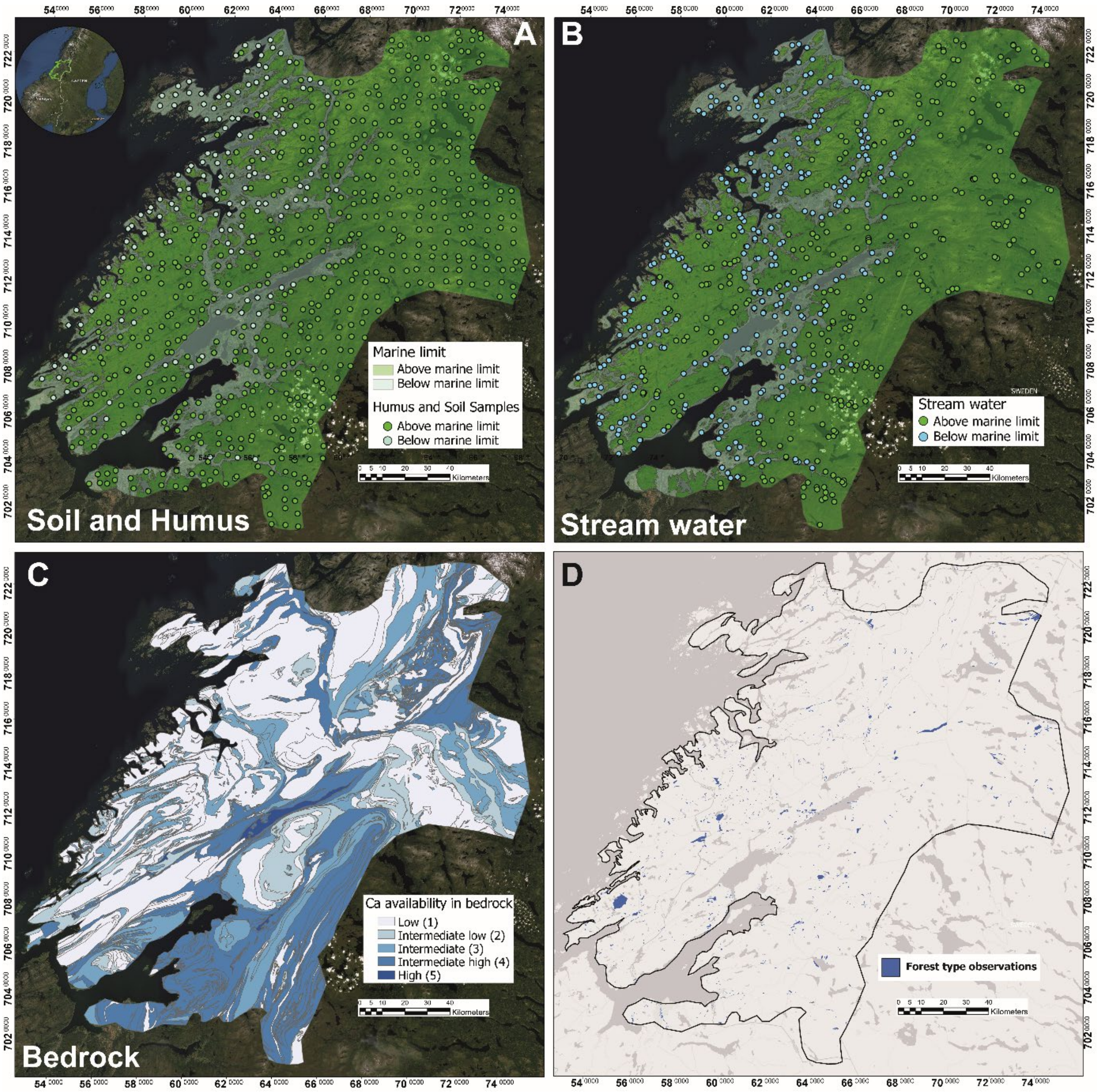

Figure 2. Coverage of the regional soil and humus (A), stream water (B), Ca availability in bedrock (C) and forest type (D) datasets.

3. Quantifying calcium availability: sources and geochemical datasets

Major, minor and trace elements migrate from the geosphere (bedrock) to the hydrosphere (e.g., streams and lakes) and biosphere (e.g., plants) through a series of mechanical (erosion) and chemical (inorganic and organic reactions) processes generally referred to as weathering (**e.g., Gadd et al. 2007; Graham, et al. 2010, Anderson, 2019; Miller, 1999**).

Unweathered rocks have a low permeability mainly given by joints resulting from thermal, tectonic, and erosional unloading processes (**Graham et al. 2010**). As meteoric water flows down joint fractures and enters the bedrock mass, chemical weathering occurs (**Meunier et al., 2007).** For example**,** ion exchange weathering in biotite (e.g., interlayered replacement of K by hydrated Mg cations; **Wahrhagtig, 1965**) induces a significant volume expansion (30 to 40%; **Graham et al. 2010**), causing the

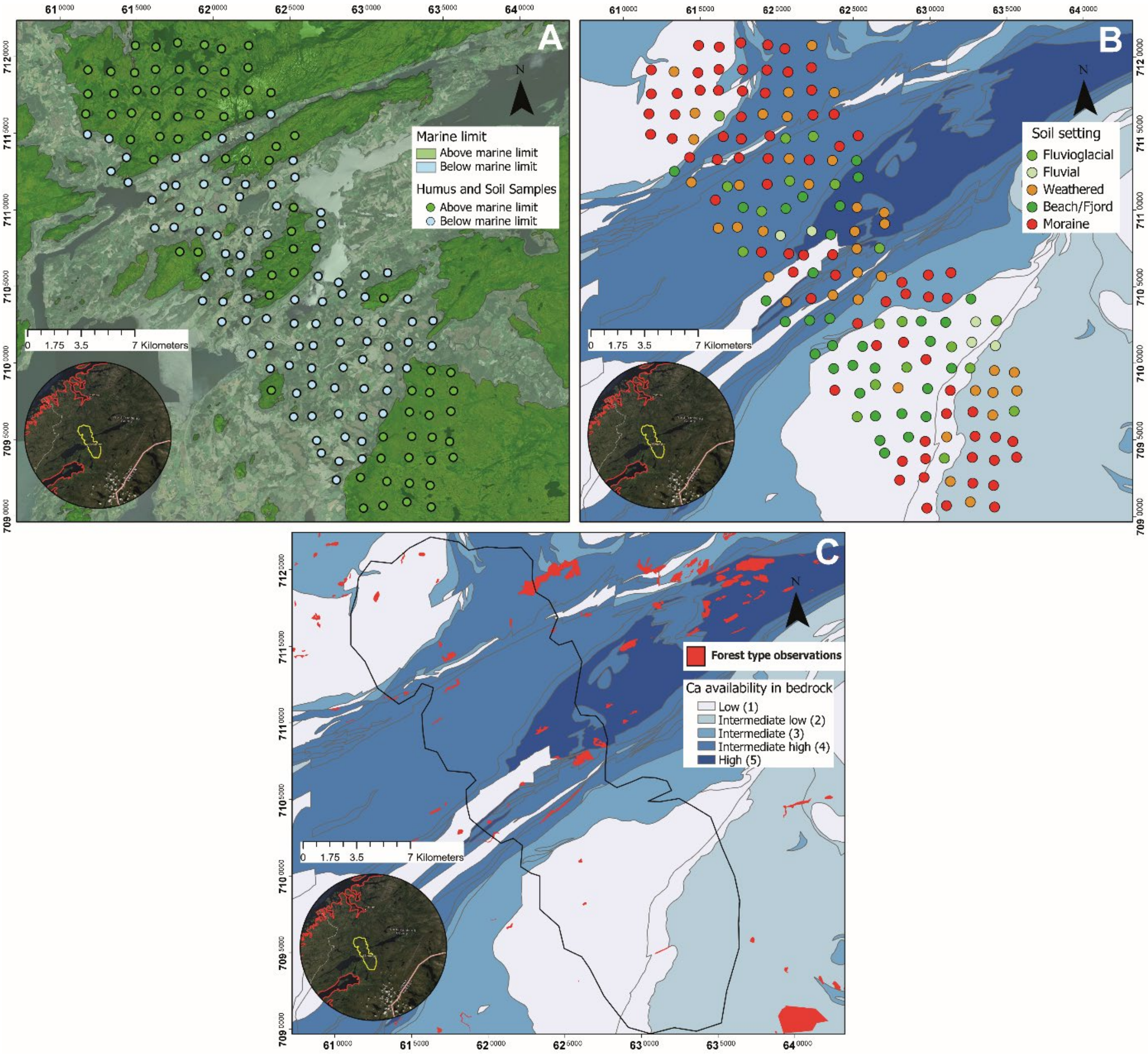

Figure 3. Coverage of the Steinkjer area soil and humus samples (A), Ca availability in bedrock map and soil settings sampled (B) and forest type data (C).

rock matrix to lose much of its mechanical strength (**Arel and Önalp, 2004**) transforming it into regolith (i.e., saprock; **Anand and Paine, 2002**). Mesofractures developed from this process significantly increase the surface area for weathering to continue (alteration of other minerals, e.g., feldspars) and induces a much higher water percolation in the regolith (**Graham et al. 2010**). Chemical weathering releases elements, such as calcium, to the meteoric waters (e.g., stream water) of a watershed constraining their chemical composition to that of bedrock units within the basin in the absence of anthropogenic contamination (**e.g., Miller, 1999**). The porous substrate of the regolith (i.e., soil) favours structural support and access to water and nutrients (e.g., Ca) for plant roots (**Graham et al. 2010**). Furthermore, the roots provide energy to a multitude of soil organisms and promote further weathering (**e.g., Graham et al., 1994**). Humus is not genetically linked to soil formation (i.e., mechanical and chemical weathering) but corresponds with dark, organic material that forms in soil when plant and animal matter decays. The geochemical composition of humus depends on various mechanisms, including the transfer from the mineral soil by root uptake in plants and return to the humus layer by leaching or decaying plant material ('vascular pump') (**Steinnes and Njåstad, 1995**). For calcium, this mechanism seems to be predominant (**Steinnes and Njåstad, 1995**).

The following sections describe the bedrock, soil, humus, and stream water datasets used to assess lime availability in terms of calcium concentration (calcium availability) at regional and local scales within northern Trøndelag.

3.1 Regional Survey

The Geological Survey of Norway has built an extensive database after decades of regional and local geochemical mapping throughout the entire country. Some of these data were acquired as far back as the 1970s and 1980s. Soil samples covering Nordland, Troms and Finnmark (sampling density of 1 sample/ per 36 km^2) were re-analysed in 2011, whereas soil and humus data used in this study were collected and analysed in 2013 (**Finne et al., 2014; Finne and Eggen, 2015; Reimann et al., 2015**), as part of the new regional geochemical mapping program launched by NGU in 2010.

Sampling locations were selected in the field, preferably close to the centre of 6 x 6 km grid cells, yielding a sampling density of 1 sample/ per 36 km^2. Soil samples were collected from a single pit in the C-horizon, primarily of till but also from weathered rock, whereas samples of the maximum 3 upper cm of humus layer samples were pooled from a minimum of 5 subsamples within an area of 100-200 m^2. The average wet weight of soil and humus samples was 1,8 kg and 1,3 kg, respectively. After drying at temperatures below 30 °C, samples were sieved through nylon mesh to less than 2 mm. The last preparation step consisted of renumbering all the samples to a random order and insert splits of a large sample of known chemical composition for quality assessment following **Eggen et al. (2019)**. A collection of previously analysed samples was also included for levelling purposes.

Analytical work was done in Bureau Veritas Mineras Laboratories (former ACME labs, Canada). For soil analyses, 15 g samples were digested in Aqua Regia and analysed by ICP-MS for 53 elements according to package 1F. From the humus samples, a 5 g portion was digested in HNO_3, then Aqua Regia and finally, analysed by ICP-MS (package 1VE2).

The stream water data (**Fig. 2B**) is a compilation of data from three campaigns carried out in 1982-83, 1989 and 1990, reported by **Ryghaug et al. (1994) and Banks et al. (2001)**. In total, samples from 638 small rivers and large streams, mainly accessible by car. Remote areas were not included for financial reasons and the sampling pattern resulting from the given restraints of watercourses and infrastructure was irregular, although estimated to 1 sample / per 30 km^2. Samples were collected during August and September, and two aliquots were filtered in the field through 0.45 µm thick Millipore filter. To one of the aliquots suprapure HNO_3 was added to achieve pH 2 for conservation. Concentrations for major and trace cations in the acidified aliquot were obtained by ICP-AES, and the anions by IC at the NGU laboratory.

A proxy for calcium availability in bedrock was obtained from **Heldal and Torgersen (2020)** 1:250000 scale map (**Fig. 2C**). In this work, lithological units were classified according to their natural calcium budget after obtaining analytical results for nitric acid extractable calcium in 1970 rock samples collected across Norway. Other observations on the occurrence of natural species overlying bedrock were also incorporated into this classification. Bedrock units were classified into five categories, where values 1 and 5 represent rocks with the lowest and highest calcium budgets, respectively. For the present study, the numerical classification was replaced by the following qualitative scale: 1 = Low, 2 = Intermediate Low, 3= Intermediate, 4 = Intermediate High and 5 = High (**Fig. 2C**).

Data for different forest types contained in northern Trøndelag was acquired from the Norwegian Environment Agency nature database map (**Miljødirektoratet, 2020**; **Fig. 2D**) and used as a proxy to correlate calcium availability in bedrock, loose material (soil and humus) and water to natural species. This dataset consists of multiple in-situ observations represented by polygons covering areas as small as 76 m^2 and up to 23 km^2. The average and median values of the area sizes reported are 0.16 km^2 and 0.04 km^2, respectively. In this report we provide informal English translations for most forest types, but the original Norwegian names are provided in **Appendix I.**

3.2 Local survey

The local survey carried out in the Steinkjer municipality has a sampling density of 1 sample / per 2.25 km^2 (1.5 x 1.5 km grid cell), where a total of 168 sites were sampled for humus and mineral soil (**Fig. 3A**). Field sampling protocols are analogous to those described for the regional soil and humus surveys and quality assurance and control protocols (QA/QC) equivalent to those described in **Eggen et al. (2019)**. Both media samples were sent to Bureau Veritas Mineral Laboratories for analytical work. Concentrations for major and trace elements in soil were obtained by the same methods described for the regional survey (restructuring in the lab gave new codes to the same procedures; 1F = AQ251, and 1VE2 = VEG05).

Given the more detailed scale study, samples could not be collected only from relatively *in-situ* soils developed over moraine sediments and weathered bedrock, but also included material from soils formed over transported sediments; for example, fluvioglacial, fluvial and beach sediments (**Fig. 3B**). To simplify subsequent statistical analysis, soils developed over fluvial sediments (only 5 locations) were included in the fluvioglacial classification

4. Calcium in different media: above and below marine limit

4.1 Regional survey

The sample distribution of the soil and humus surveys show that 82% of the data was taken in areas above the marine limit (**Fig. 4A**). In general, areas below the marine limit are underlaid by lithologies having lower calcium availability (≈75% have low to intermediate low values; **Fig. 4B**), whereas samples taken in areas above the marine limit overlay lithologies having higher calcium availability (≈60% have intermediate to high values; **Fig. 4B**). In both media, calcium and other major element concentrations are largely equivalent, but the calcium median values are slightly higher in samples taken in areas above the marine limit (**Fig. 4C, D**). Due to the discrete nature of the bedrock calcium availability iscale, calculating a statistical correlation between this and overlying mineral soil and humus is not possible. A proxy to evaluate such correlation is provided in **Figure 5**. If the increase in calcium concentration in soil and humus coincides with the bedrock calcium availability classification, then an overall positive correlation between the overlying loose material and the bedrock can be inferred. The greater the contrast between low and high calcium concentrations spatially associated with equivalent calcium indexes in bedrock, the higher the correlation between bedrock and the overlying media (**Fig. 5**). Based on this, calcium budgets in bedrock and humus (**Fig. 5B**) have a better spatial correlation relative to soil and bedrock (**Fig. 5A**).

For the stream water survey, the sampling density for areas above and below the marine limit is equivalent (**Fig. 6A**). In the same way, both areas contain samples taken over lithologies having analogous calcium availability (**Fig. 6B**). Most areas below the marine limit are slightly enriched in calcium and other major elements content (**Fig. 6C**).

The correlation between stream water and bedrock calcium budgets appears higher than that of humus and soil (**Fig. 5C**). However, it is noted that the largest cluster of samples having the highest calcium concentrations represent streams draining farming areas (**Figs. 7A, B**). A potential anthropogenic disturbance is further indicated by results obtained in easternmost portion of the studied area, which is mainly located above the upper marine limit. This area is highlighted in the bedrock calcium availability map, and humus and soil surveys as one with a high calcium budget, while the stream water survey indicates more moderate calcium enrichments. (**Figs. 8A, C, E**).

4.2 Local survey

Humus and soil samples obtained in areas above and below the marine limit represent 45% and 55% of the dataset, respectively (**Fig. 9A**). A slightly higher proportion of samples taken above the marine limit fall in areas with intermediate low to high calcium availability index in bedrock relative to samples taken in areas below the marine limit (**Fig. 9B**). Although soil material was obtained from areas covered by transported soils (**Figs. 3B; 9C),** over 60% of the sample suite was collected over moraine sediments (40%) and weathered bedrock (20%) (**Fig. 9C**). Soil samples taken below the marine limit are generally more enriched in potassium and magnesium relative to those taken in areas above the marine limit (**Fig. 9D**). Similarly, other elements such as sodium, phosphorous, calcium, aluminium, and iron have slightly higher median values in areas below the marine limit, but in all cases, data distributions in both areas are indistinguishable (**Fig. 9D**). Only titanium is enriched in the areas above the marine limit (**Fig. 9D**). Soil samples taken over moraine sediments show similar distributions for major elements, where sodium, phosphorous, calcium, aluminium and iron have comparable medians and overall data distributions, potassium and magnesium are slightly enriched in areas below the marine limit, and titanium is more abundant in areas above the marine limit (**Fig. 9E**).

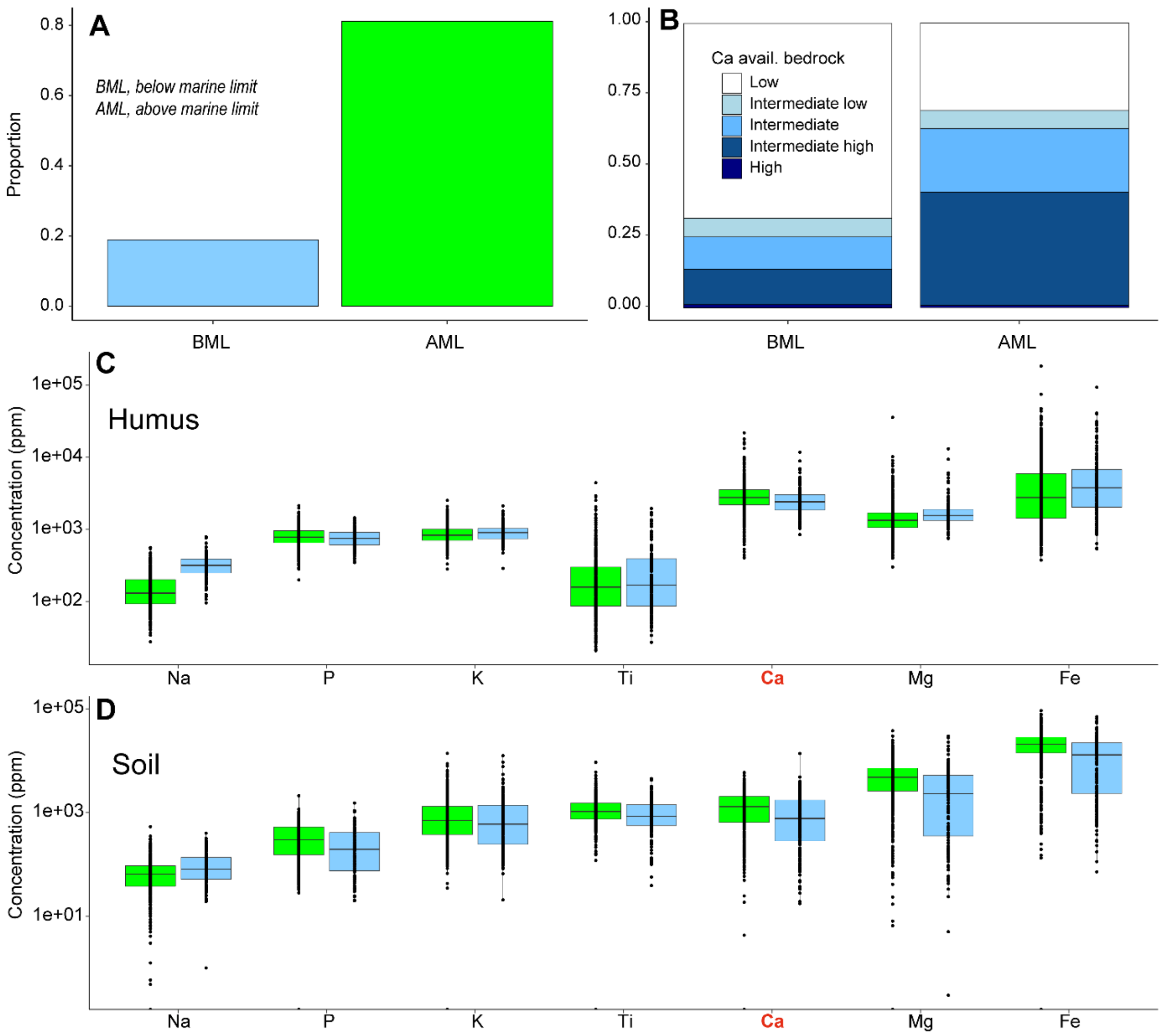

Figure 4. Humus and soil regional surveys. A) Percentage of samples obtained in areas above (AML) and below (BLM) the marine (BML) limit. B) Percentage of samples that fall into each of the five categories defined by Heldal and Torgersen (2020) in their calcium availability bedrock map. Distribution of major element concentrations in humus (C) and soil (D). Calcium concentrations are highlighted in red.

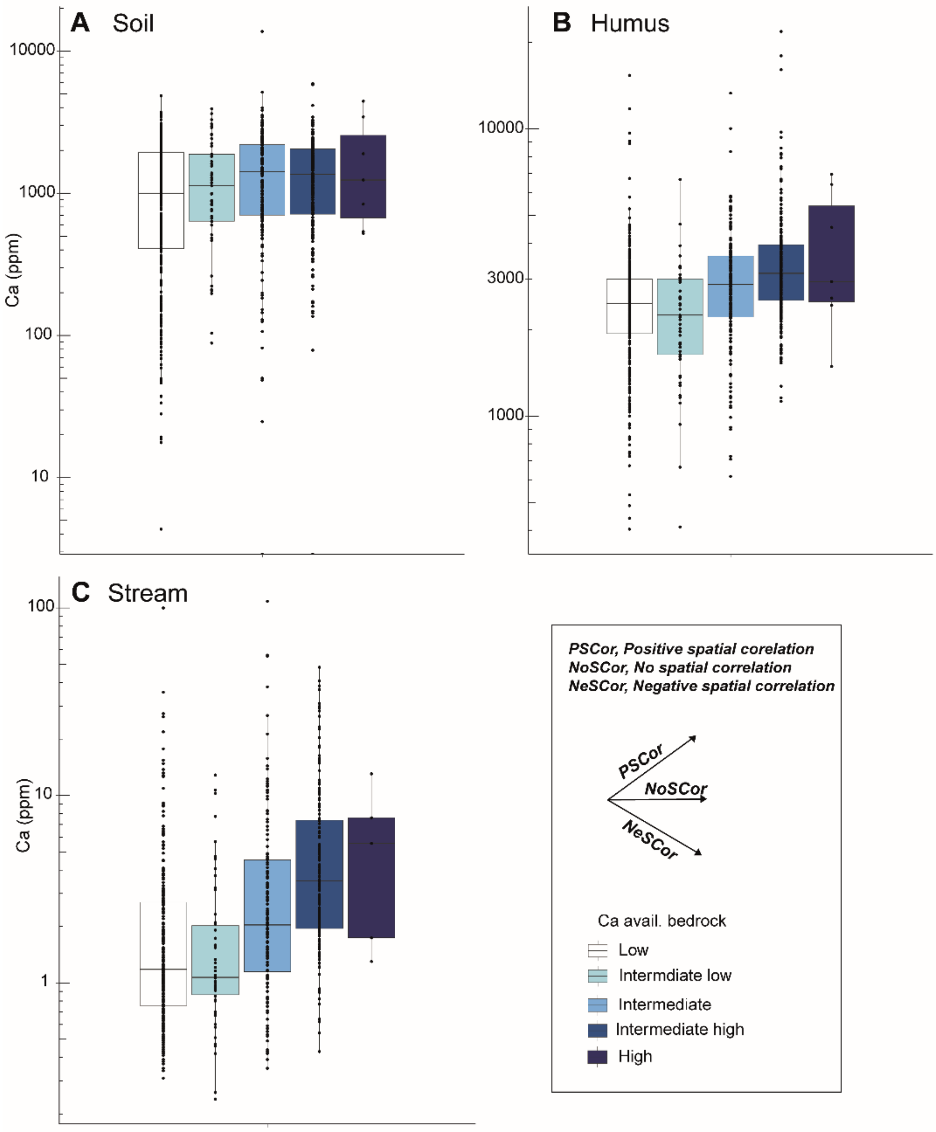

Figure 5. A) Distribution of Ca concentrations from soil (A), humus (B) and stream water (C) classified according to their location in the calcium availability bedrock map of Heldal and Espen (2020). The greater the increase of the boxplot calcium distributions from left to right, the stronger the spatial correlation between a media type (soil, humus, and stream water) and bedrock.

In the humus samples (**Fig. 9F**), phosphorous, sodium, potassium and magnesium have comparable median and data distributions, whereas titanium, iron, aluminium, and calcium are slightly enriched in areas below the marine limit.

Figure 10 displays the major element concentrations of soil and humus separated by depositional setting types. Soil samples collected over weathered bedrock are systematically depleted in all major elements relative to those collected over moraine, glaciofluvial and beach/fjord sediments (**Figs. 10A**). However, except for titanium, these systematic depletions were not found in the humus data (**Fig. 10B**). Further inspection of the soil data shows that this depletion is not an analytical artefact as X, random and ordinary versus duplicate sample plots (among other QA/QC criteria) support its statistical validity (**Appendix II**).

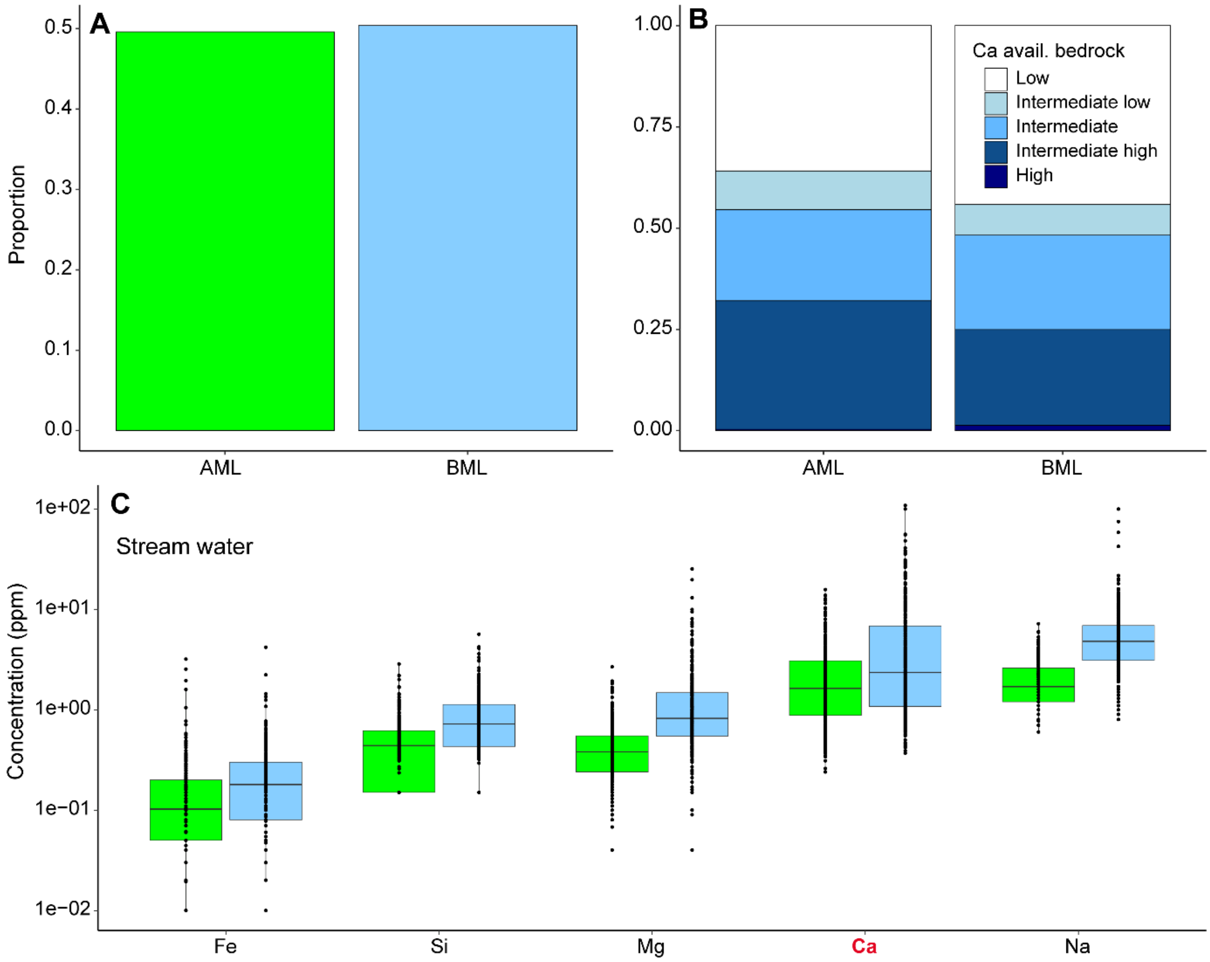

Figure 6. Stream water regional survey. A) Percentage of samples obtained in areas above (AML) and below (BML) the marine limit. B) Percentage of samples that fall into each of the five categories defined by Heldal and Espen (2020) in their calcium availability bedrock map. C) Distribution of major element concentrations is stream water. Calcium concentrations are highlighted in red.

The geochemical depletion in samples collected over weathered bedrock cannot be attributed to a biased sampling over specific lithological units as soil samples taken over moraine and weathered bedrock material were proportionally taken over roughly analogous lithological units (**Fig. 11A**).

Moreover, a larger proportion of the samples taken over weathered bedrock overlay lithologies having higher calcium availability in bedrock relative to those of moraine and transported soils (**Fig. 11B**). It is recognized that a larger proportion of weathered soil samples were taken over areas above the marine limit relative to samples from transported soils (**Fig. 11C**). However, samples collected over weathered bedrock and moraine sediments were taken in proportionally equivalent locations above and below the marine limit (**Fig. 11C**). Since the major element depletion is only observed in the weathered bedrock soil samples, a biased sampling over areas above the marine limit cannot explain this geochemical anomaly.

Alternatively, this geochemical depletion may result from a relatively larger grain size (closer to 2 mm) of the soil material collected over weathered bedrock.

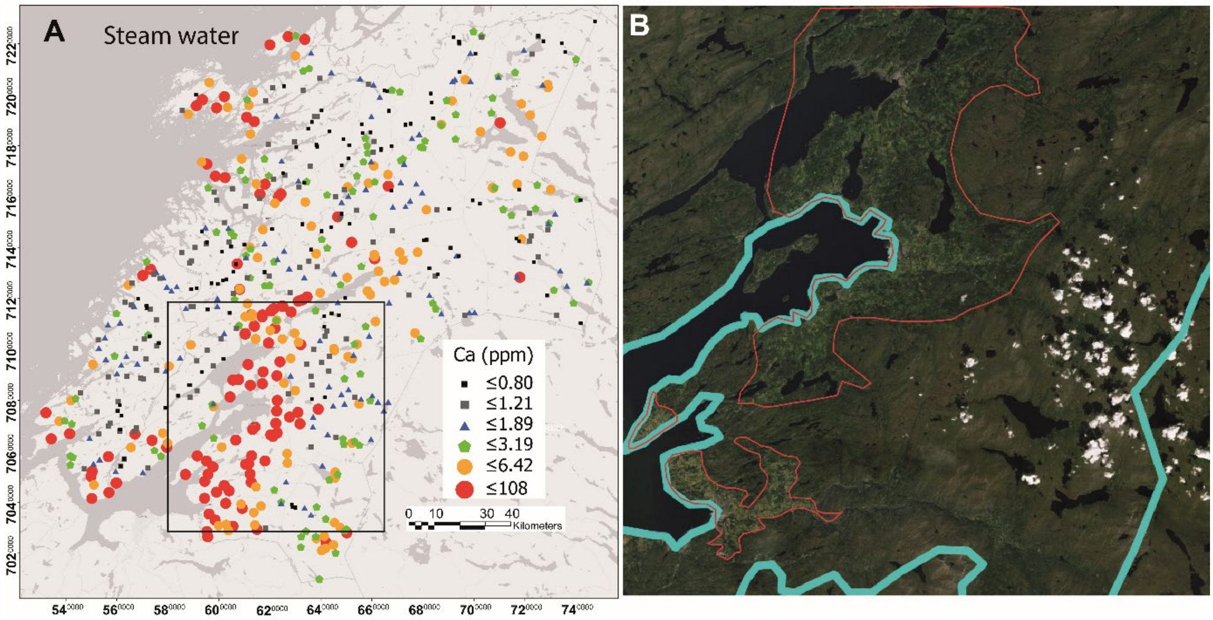

Figure 7. A) Calcium concentrations of the regional stream water survey in northern Trøndelag. B) Inset from A (black square) showing the location of farmland (red line) and the contour of the northern Trøndelag area (light blue). A large cluster of Ca-rich samples plot over farmland potentially indicating anthropogenic contamination.

Although there are no quantitative data, it was noticed that soil samples derived from weathered bedrock tend to have a coarser grain size fraction compared to moraine and transported soils. An overall larger grain size, relative to the other soil types, may have limited the digestion of most major elements in aqua regia, resulting in their systematic depletion in soil samples collected over weathered bedrock.

As a proxy to evaluate the calcium concentration from *in-situ* soil settings and its spatial correlation with the bedrock calcium budget and areas above and below the marine limit, we used the moraine soil samples. These samples are distributed throughout the survey area and cover most types of lithological units (**Fig. 3B**). In both datasets, total soil and moraine setting samples, the spatial correlations between this media and bedrock are more ill-defined than humus and bedrock (**Figs. 3B; 12,13**). Like the regional survey, the Steinkjer data also shows a more significant spatial correlation between humus and bedrock calcium budgets and roughly equivalent calcium contents in areas above and below the marine limit.

4.3 Potential impact of grain size in geochemical analyses

From these results, two main observations can be made. First, despite having been taken from transported soils, the calcium contents of humus samples resemble those of the underlying bedrock better than those of soil samples. This behaviour has been recognized at the regional and local scale surveys, suggesting that humus could be a more reliable media to characterize the underlying lithological units in terms of calcium

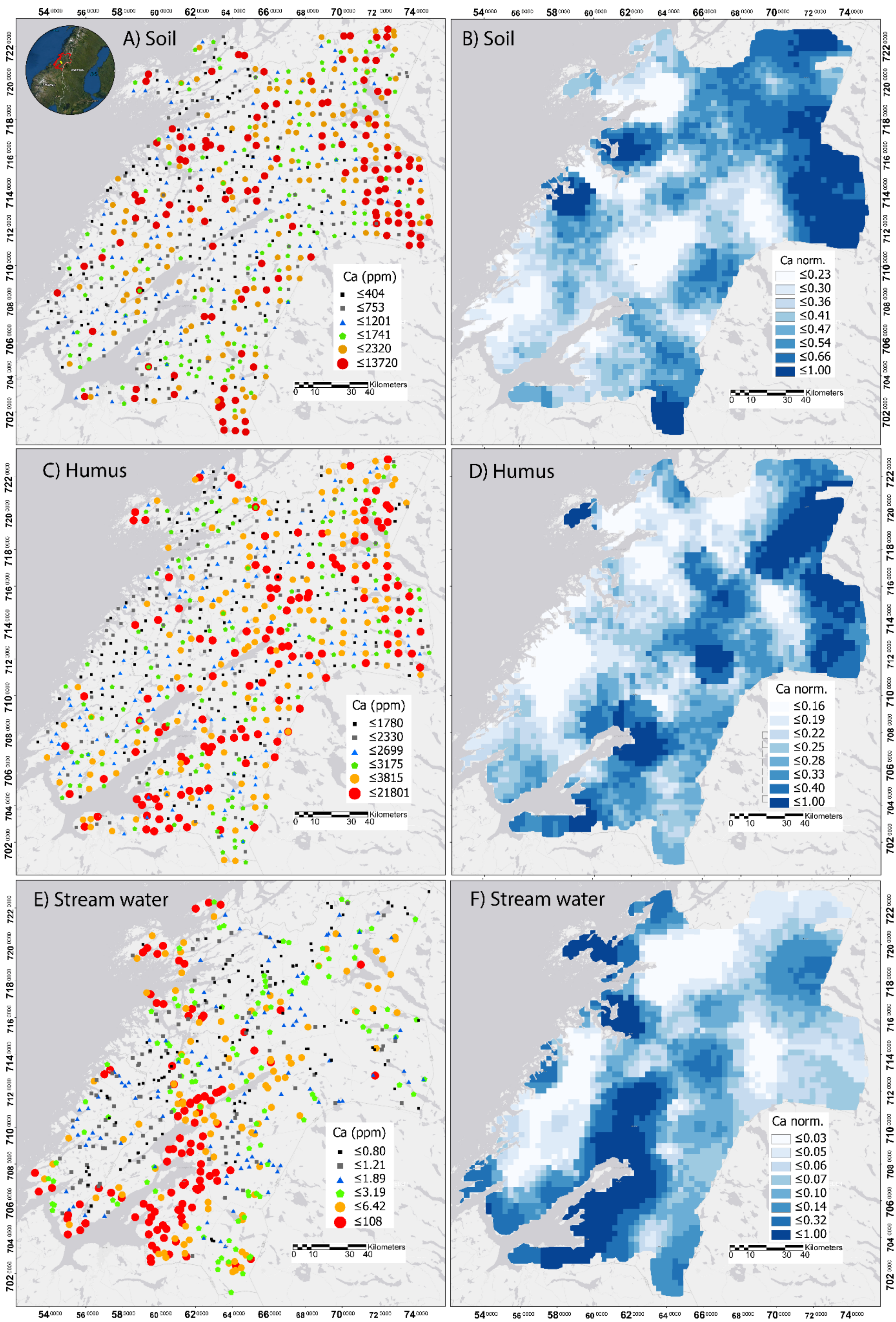

Figure 8. On the left are shown the calcium concentrations of soil (A), humus (C) and stream water (E), whereas on the right (B, D, F), calcium concentrations are interpolated using the kriging method to a 3 km x 3km bin size and normalized to values between 0 and 1 using equation (1).

availability. In turn, this may have significant relevance for future activities, for example, mineral exploration and environmental assessments. Second, the lack of major element depletions in humus samples from the Steinkjer survey further suggests the correlation between grain size and geochemical depletions in the coarser-grained samples taken over weathered bedrock. Due to its nature (in-situ decay of organic matter), humus is a fine-grained and relatively homogeneous material. Conversely, soil results from mixed mechanical and chemical weathering; hence, soil samples have a larger grain-size heterogeneity than humus. If the geochemistry of soil is mainly given by the composition of the more soluble (in aqua regia) finer-grained particles (<< 2 m), then variable proportions of fine- and coarse-grained (≈ 2 mm) material for samples taken over the same lithological unit could achieve largely distinct analytical results.

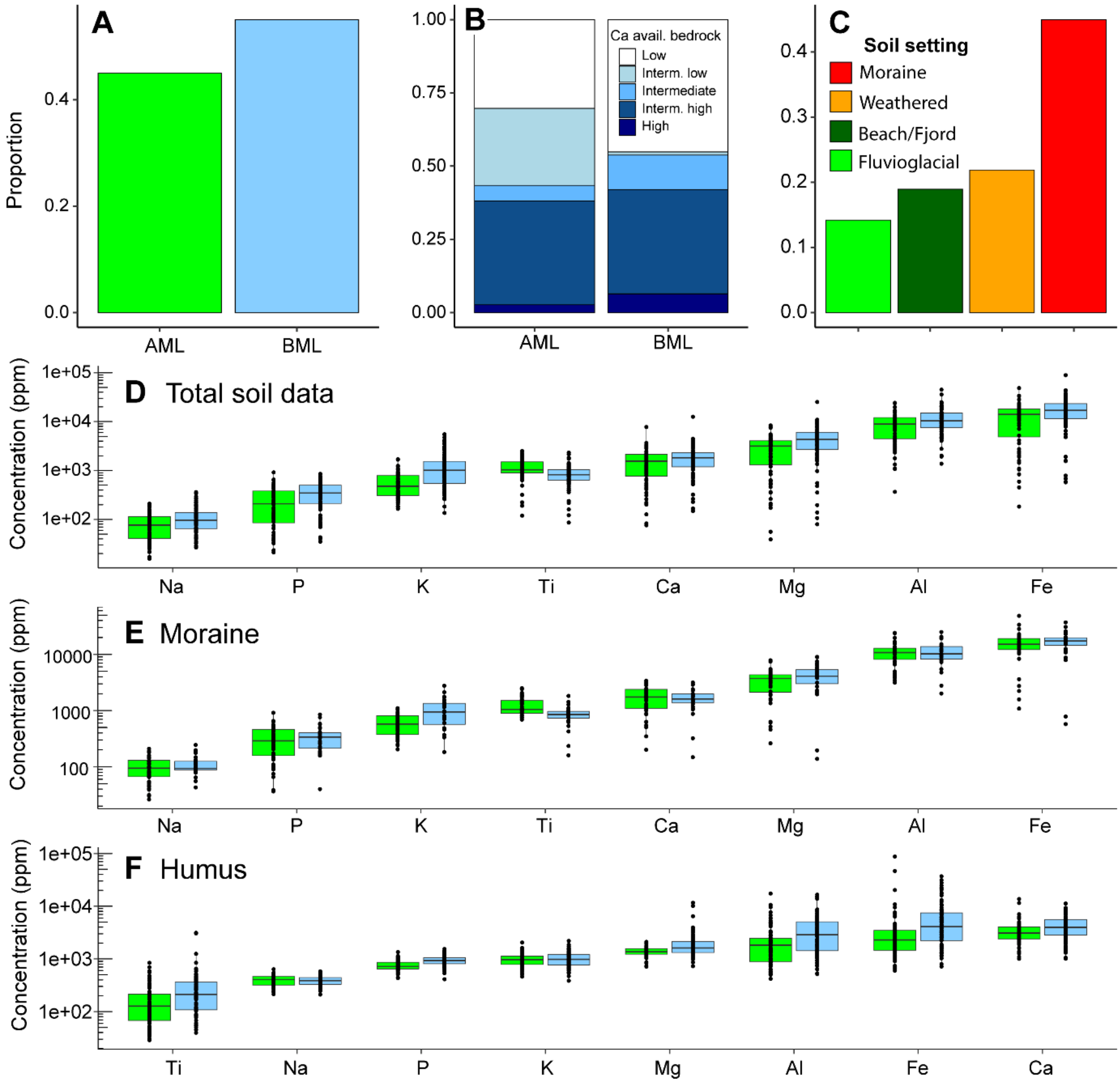

Figure 9. Steinkjer humus and soil surveys. A) Percentage of samples obtained in areas above (AML) and below marine (BML) limit. B) Percentage of samples that fall into each of the five categories defined by Heldal and Torgersen (2020) in their calcium availability bedrock map. C) Percentage of soil samples taken over sediments from different depositional settings. Distribution of major element concentrations in all (total) soil (D), moraine (E) and humus (F) samples.

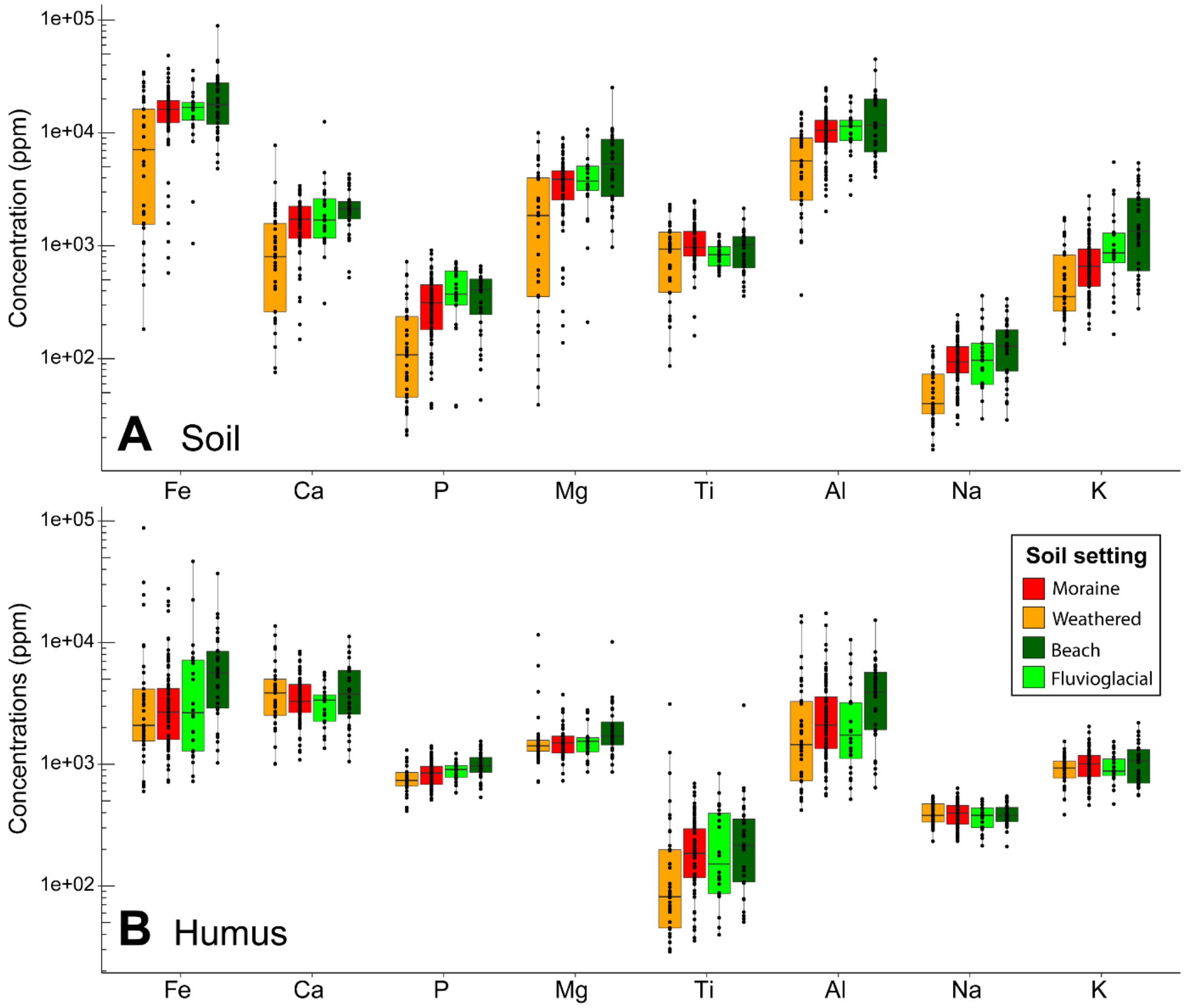

Figure 10. Steinkjer survey. A) Major element concentrations of soils taken over distinct depositional settings. Samples taken over weathered bedrock are consistently depleted in all major elements relative to soil material collected in other settings. B) Major element concentrations of humus taken over the distinct soil settings. Humus taken over weathered bedrock do not show the strong major element depletion observed in the soil samples.

Ultimately, this could significantly disturb the geochemical signature of soil samples relative to their source (the underlying bedrock), blurring their spatial correlation.

On the other hand, the lack of a significant grain size variation, such as that expected for humus samples, precludes that elements are partitioned in minerals contained in coarser-grained (closer to 2 mm); thus, less soluble particles are underrepresented through analytical measurements. This will lead to a closer spatial correlation between calcium (and other major and trace elements) in humus and bedrock relative to that of calcium in soil and bedrock as recognized in this study.

5. Integration methodology

5.1 Data preparation

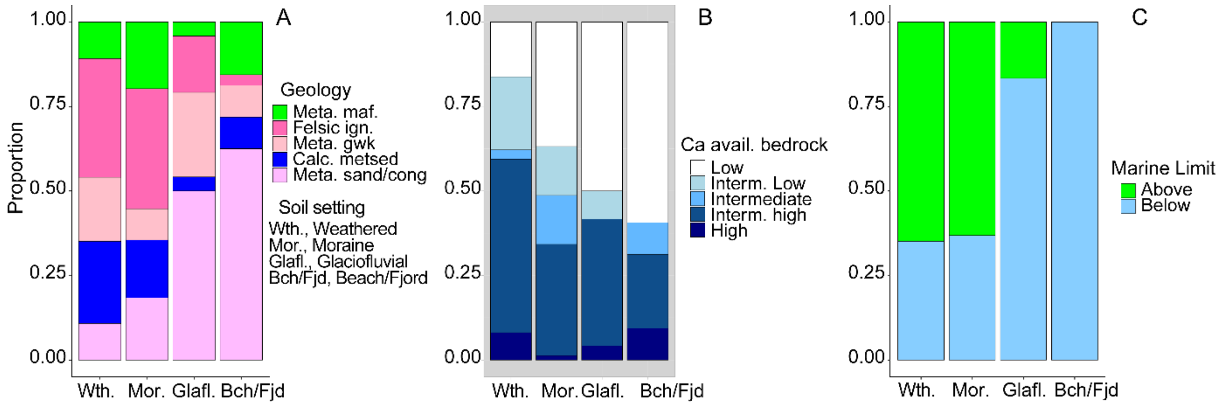

Figure 11. Steinkjer survey. A) Proportion of samples taken over different lithologies for each soil setting. Abbreviations. Meta. Maf., metamafic rock; Felsic ign., felsic igneous; Meta. gwk, metagraywacke; Kalk. Metased, calcium-rich metasediments; Meta. sand/cong, metasandstone/-conglomerate. B) Percent of samples for each soil setting that fall into each of the five categories of the Heldal and Torgersen (2020) calcium availability bedrock map. C) Percentage of samples for each soil type obtained in areas above (AML) and below (BML) marine limit.

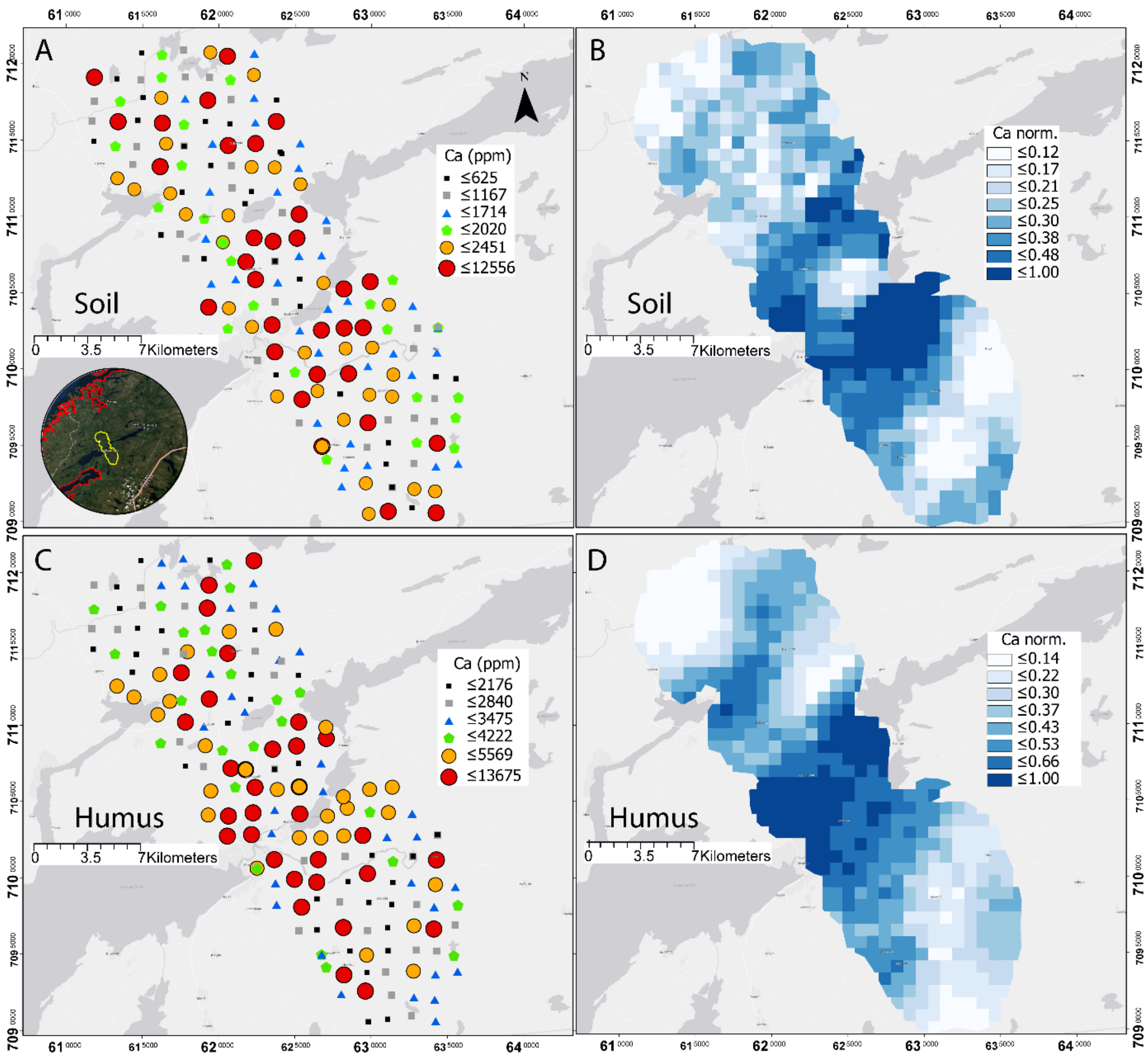

Figure 12. Steinkjer survey. On the left are shown the calcium concentrations of soil (A) and humus (C), whereas on the right (B and D), calcium concentrations are interpolated using the kriging method to a 0.8 km x 0.8 km bin size and normalized to values between 0 and 1 using equation (1).

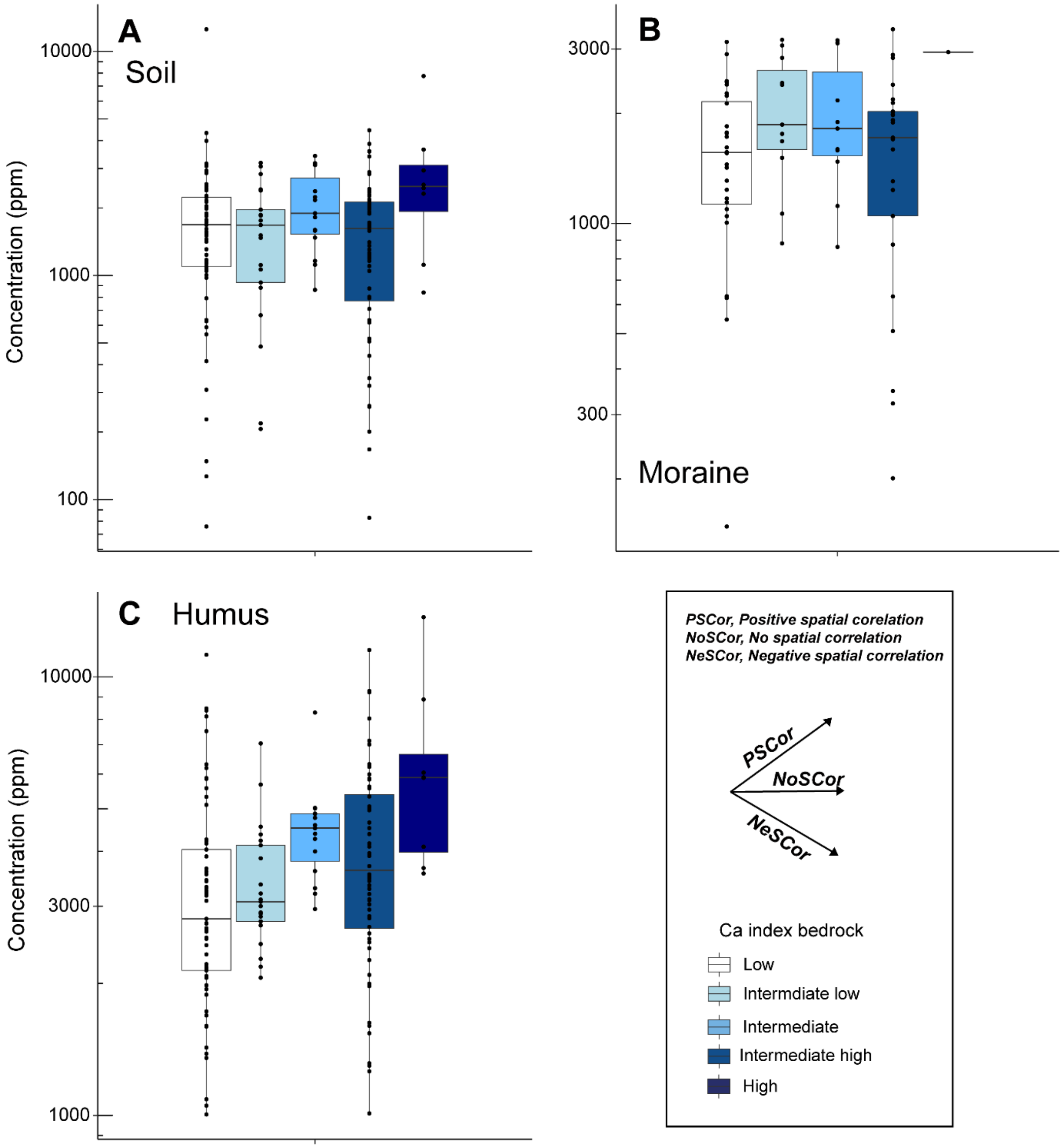

Figure 13. A) Distribution of calcium concentrations from soil (total data) (A), moraine (B) and humus (C) samples classified according to their location in the calcium availability bedrock map (Heldal and Espen,2020). The larger the increase of the boxplot calcium distributions from left to right, the stronger the spatial correlation between a media type and bedrock.

Data preparation consisted of the rasterization of all media layers using bin sizes representing half of the sampling density. The soil, humus and stream sediment regional databases were interpolated to a 3 km x 3 km (1 data point per 9 km^2) grid bin size (**Fig. 8**), whereas the soil and humus local surveys were interpolated to a 0.8 x 0.8 km (1 data point per 0.6 km^2) grid cell size (**Fig. 12**), in both cases, using the kriging method. In the same way, the Heldal and Torgersen (2020) bedrock calcium availability map was rasterized to equivalent bin sizes for each survey scale. The forest-type layer was rasterized to a grid cell of 9 x 9 m (80 m^2) as this is roughly the area of the smallest polygon representing an in-situ observation (**Fig. 14A**). The forest-type raster maps were then converted into point maps (**Fig. 14B, C)** to facilitate further statistical analysis and spatial correlations with the geochemical and bedrock layers.

5.2 Integration of layers of evidence: soil, humus, stream water and bedrock

The integration of the multimedia databases was done using Continuous Fuzzy Logic (**Kuratowski and Mostowski 1976**) and Index Overlay (**Bonham-Carter 1994**), two approaches often used on the elaboration of mineral potential maps (**e.g.**, **Montsion et al. 2019**). Calcium parameters (i.e., concentrations and bedrock availability index) for each layer are normalised using the following equation:

$$t = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where *t* is the normalised value, *x* is the original value of the data point or bin, x_{min} is the minimum and x_{max} is the maximum values in the data. This equation transforms values to range from low (t = 0) to high (t = 1) calcium availability index. By doing this, the map preserves the continuous nature of the data layers rather than classifying datasets into ranges. In this case the normalised layers were then weighted using a weighting factor (w), which was determined by three criteria: coverage, calcium budget available for overlying plant species (herein forest types), and representativeness of in-situ natural processes. Each layer of evidence was assigned a weight (*w*) and subsequently, all were added together using similar principles to those of the Index Overlay method to produce an integrated calcium availability map using the equation below. In this equation, *X* is the integrated Ca availability value and *t* is the normalised value from each media layer.

$$X = \sum_{i=1}^{n} (t * w)$$

5.2.2 Weighing layers of evidence: Regional and Local scale surveys

For the regional scale survey, the humus and soil samples were assigned the highest weights, 0.8 for each layer. These datasets have a consistent distribution throughout the area of study, and their sampling sites were carefully chosen to obtain *in-situ* material and avoid (as much as possible) any potential geochemical disturbance derived from human activity (e.g., farming). In addition, soil represents the largest calcium reservoir for plants (and their related ecosystems). Humus preserves the geochemical signature of *in-situ* decaying organic material (e.g., plants), which provides further insights into the availability of calcium in the underlying soil and bedrock. The bedrock calcium availability layer was given a lower weight of 0.4. Although bedrock is the ultimate source of calcium for the biosphere, the former rarely represents a direct calcium reservoir for plants, which often acquire their nutrients directly from the soil. In addition, the calcium availability indexes assigned for the lithological units in northern Trøndelag area are based on a national scale study. Therefore, these do not represent *in-situ* bedrock calcium budget, but an estimate based on an average of similar lithologies sampled elsewhere across Norway. The lowest weight was given to the stream water layer (w= 0.2) as it has an irregular distribution of the sampling sites resulting in large unsampled areas (up to 344 km^2), as well as its high potential for contamination due to nearby farming. The regional integrated calcium availability map (ICA) is shown in **Figure 15A**.

For the local scale survey, the humus and soil layers were given distinct weights of 0.8 and 0.2 given the soil setting-bias indicated by the geochemical results. Analogous to the regional survey, the bedrock layer was also given a weight of 0.4. The Steinkjer survey integration results are shown in **Fig. 15B**

6. Spatial correlation among media layers and the integrated calcium availability map with forest types

6.1 Limitations of the approach

The most significant limitation to interpreting the spatial correlation between natural species and ICAs is the distinct scale and survey methods by which geoscientific and ecological data are collected. In the study area, forest-type observations correspond to unevenly sized (m^2 to km^2) and distributed areas across northern Trøndelag (**Fig. 2D**). Larger areas are more statistically robust (i.e., more points), but if these are constrained to a geographical zone, data are less indicative of a regional correlation of forest-types with the ICA (and the other media layers). The constraint introduces a significant sampling bias when interpreting their spatial correlations. In addition, several forest types can be found in a single 3 km x 3 km bin of the ICA (**Fig. 14D**). As a result, lithological changes and variations in the loose material and stream water geochemistry, which may be linked to the emplacement of distinct forest types, cannot be resolved within a single 3 km x 3 km bin. Despite these limitations, we find the approach implemented in this study as a robust first-order tool to identify potential affinities of forest types with areas having variable calcium budgets. Besides, our methodology is dynamic so that the more observations are introduced to the forest type layer, the more accurate correlations with the ICA, calcium in loose material and bedrock will be achieved.

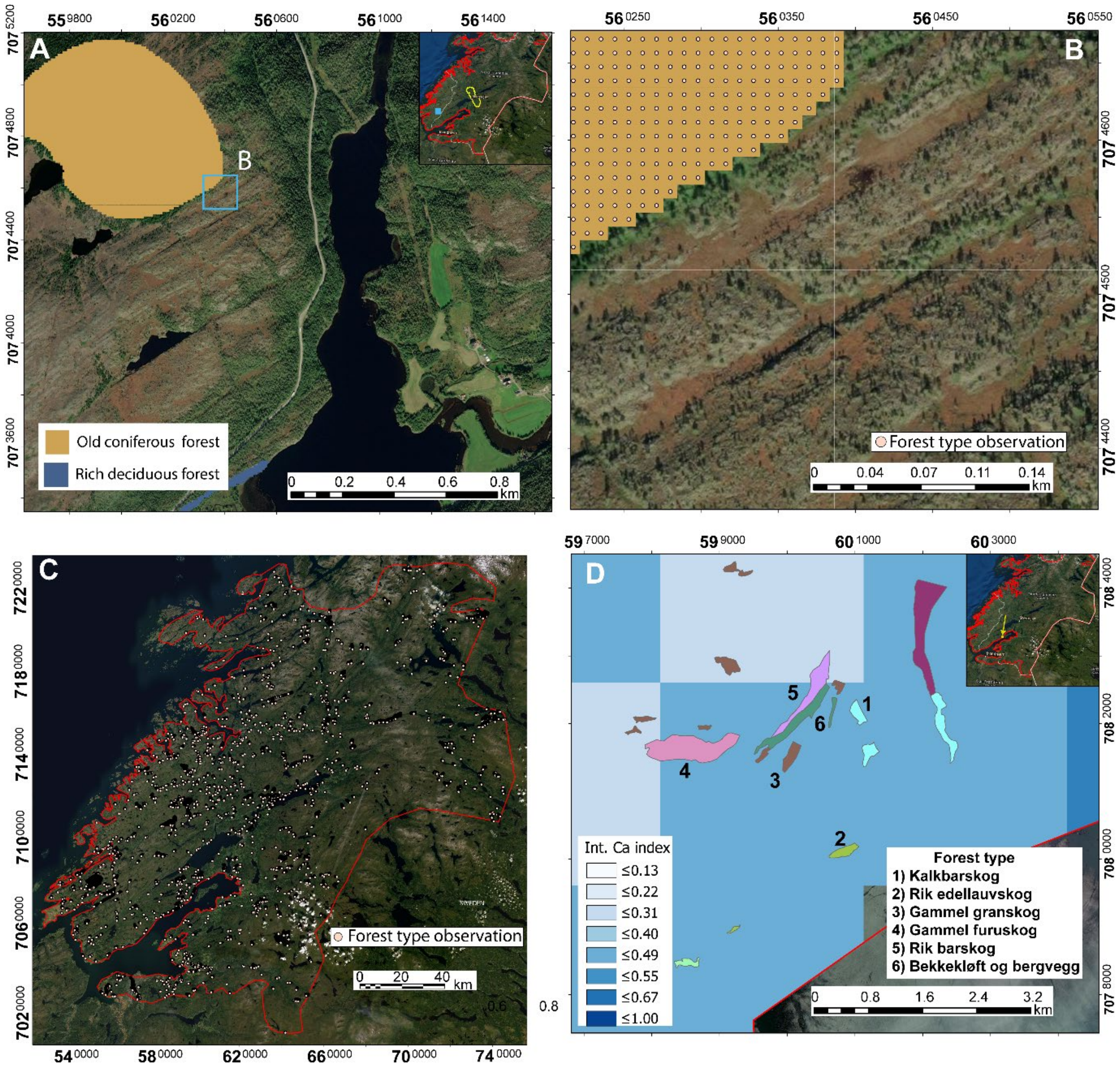

Figure 14. A) Rasterized polygons and derived point map (B) of the forest type layer. C) Forest type species point map for northern Trøndelag. D) Occurrence of various forest types in a single 3 km x 3km bin from the integrated calcium availability map.

6.2 Calcium availability and forest type: regional scale

Figures **16** and **17** (and tables given in **Appendices III and IV)** show the proportions for each forest type that fall over areas within low to high calcium availability in terms of soil, humus, bedrock and ICA, and their location regarding the marine limit. Moreover, **Figure 17** illustrates the number of points (a proxy for the area covered) and in-situ observations (i.e., polygons) recorded for each forest species. In these figures, continuous data scales for different media and ICA were transformed into discrete scales by classifying the data into five quantiles, where the first and fifth include the lowest and highest calcium availability values, respectively.

Three forest species, out of the 21 recorded in northern Trøndelag, are inferred to have a higher affinity with calcium, the lime forest (Lf; Kalkskog), lime coniferous forest (LCf; Kalkbarskog) and lime forest with boreal deciduous tree (LCBf; Kalkskog med boreale lauvtrær); hence these can be used to evaluate the validity of this integrated approach and as calibration criteria to re-adjust weights assigned (if needed) to the input layers. However, the number of in-situ observations for these forest types varies up to two orders of magnitude. The Lf has been identified in 142 sites, whereas the LCf and LCBf are recognized only in 49 and 5 sites, respectively.

From all three, the LCBf has the largest proportion of data in areas with intermediate-high to high calcium budgets for most media layers and the highest ICA median value for all forest species considered (**Figs. 16A-D; 17A**). Calcium availability in soil has a lower spatial correlation with LCBf as the majority of data plot in areas with intermediate (85%) calcium budgets (**Fig. 16A**). The Lf and LCf have a lower but still significant association with calcium in various media and the ICA. Over 80% of the LCf falls into areas where humus has intermediate high and high calcium availability values, but in bedrock and soil the percentages are much lower, 50% and 38%, respectively (**Figs. 16A, C**). Despite the latter, in both cases, a little over 50% of the bedrock and soil data is contained in areas with intermediate to high values. The ICA results show that around 75% of LCf data is contained in areas having intermediate to high calcium budgets, with an overall 50% plotting in intermediate-high and high calcium zones (**Fig. 16D**). Majority of the Lf bedrock and humus data (85%) plot over areas with intermediate to high calcium budgets (**Figs. 16B, C)**; in both media, 50% of the data is contained in areas with intermediate-high and high calcium availability values (**Figs. 16B, C)**. Like the LCBf and LCf, the Lf soil data exhibits a much lower spatial association with calcium concentration as slightly less than 50% of the data plots in areas with intermediate to high calcium availability and just over 25% in areas with intermediate-high to high values (**Figs. 16A)**. In terms of the ICA, around 75% of the Lf data plots in areas with intermediate to high calcium budgets with almost 50% contained in zones with intermediate-high to high values (**Fig. 16D)**.

In summary, for all three Ca-rich forest species, the calcium budgets indicated in humus and bedrock were higher than those of soil where in the former two media and the ICA map over ≥75% of data plots in areas with intermediate to high calcium budget.

Other forest species recognized in ≥10 locations that exhibit ≥60% data plotting over areas with intermediate to high ICA, humus and bedrock Ca budgets are old spruce forest (Gammel granskog), rook gorge and rock wall (Bekkekløft og bergvegg), gray hedgegrow forest (Gråor-Heggeskog), rich-coniferous forest (rik Barskog), floodplain forest (flommarksskog), and birch forest with perennials (Bjørkeskog med høgstauder). Like the Ca-rich forest species, calcium enrichment is less significant in soil data. The coastal spruce (kystgranskog), pine (kyfurskog), old pine (gammel furskog) and old poor noble deciduous (gammel fattig edellauvskog) forest species are normally located (>60%) in areas with low to intermediate ICA and bedrock calcium availability values and have variable calcium budgets for humus and soil (**Figs. 16A-D; 17A)**.

6.3 Calcium availability and forest type: local scale

In Steinkjer, only seven forest types have been recognized in 27 locations distributed across the surveyed area. Similar to the regional survey, figures **18** to **19** (and tables **in Appendix III and IV)** show the proportions for each forest type that falls over areas having low to high ICA and calcium availability in terms of soil, humus and

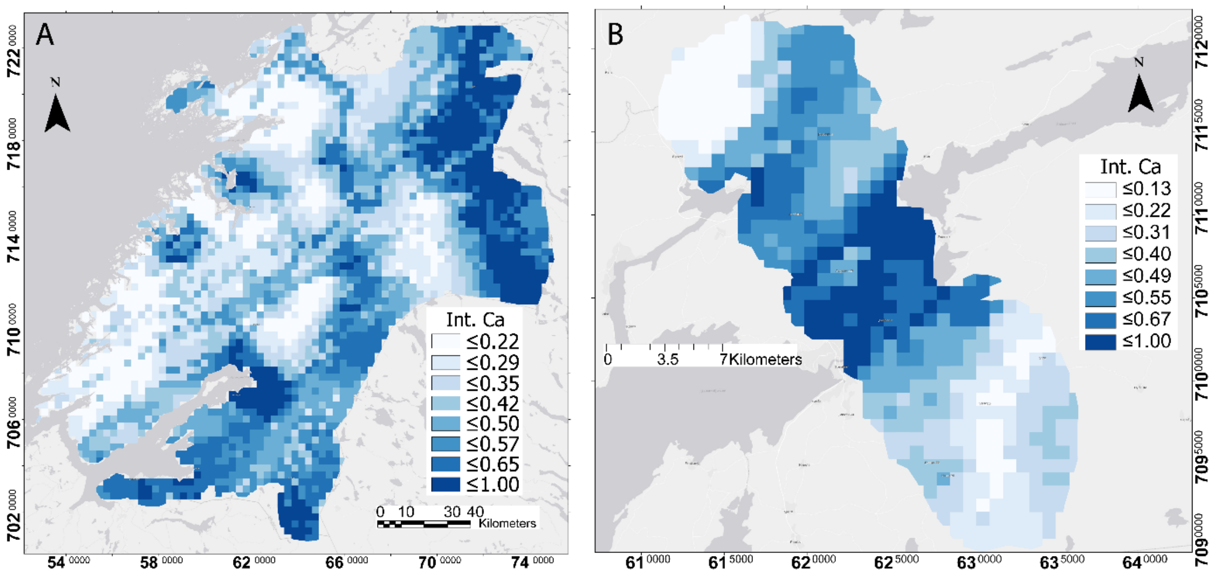

Figure 15. Integrated calcium availability maps from the regional (A) and local scale surveys (B). The media layers were integrated using equation (2).

bedrock, and their location regarding the marine limit. Also, **Figure 19** shows the number of points and in-situ observations reported for each forest species.

The lime forest (kalkskog) achieves the highest median value in the ICA map, but other under-represented (< 5 locations) forest types such as the rain forest (regnskog), hardwood forest (rik edellauvskog), and gray hedgegrow forest (Gråor-heggeskog) also achieve high values in the ICA (**Fig. 19A**). From all forest types, only the lime forest has been recognized in more than ten localities (*n*= 11).

Notably, this forest type achieved the highest ICA values, and has around 60% data located in areas having intermediate to high calcium budgets for bedrock, soil, and humus (**Fig. 18A-D**). These results further suggest that the integration approach is also valid at a local scale. However, the limited representativeness of the other forest species (≤5 localities) in the surveyed area may result in an under- or overestimation of their true affinity for calcium. In general, ≥50% of data for these forest types is contained in areas with intermediate to high calcium availability in the ICA, humus, and bedrock maps (**Fig. 18A-D**).

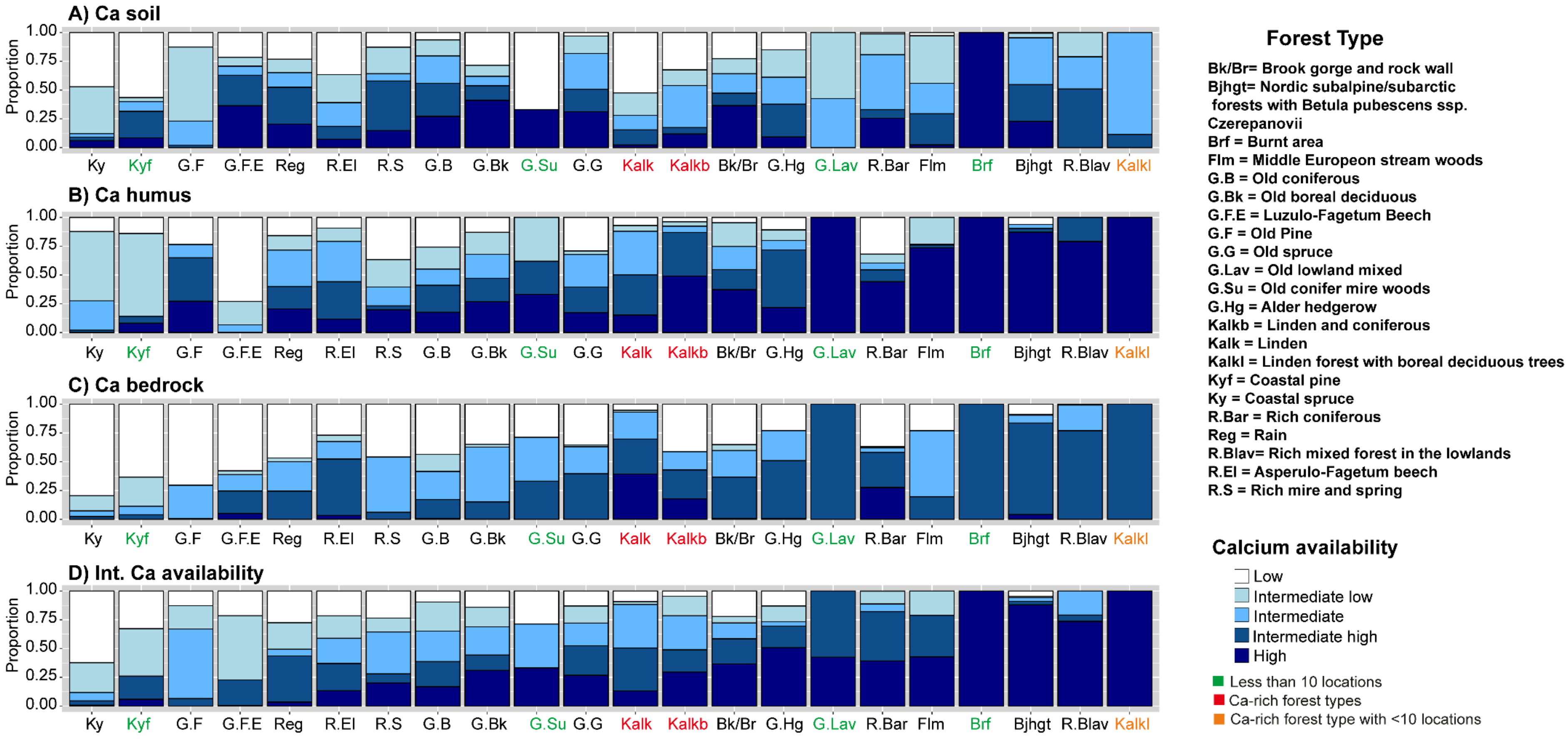

Figure 16. Regional survey. Stacked bar plots showing the proportions for each forest type in terms of their occurrence in the normalized soil (A), humus (B), bedrock (C) and integrated (D) integrated calcium availability maps.

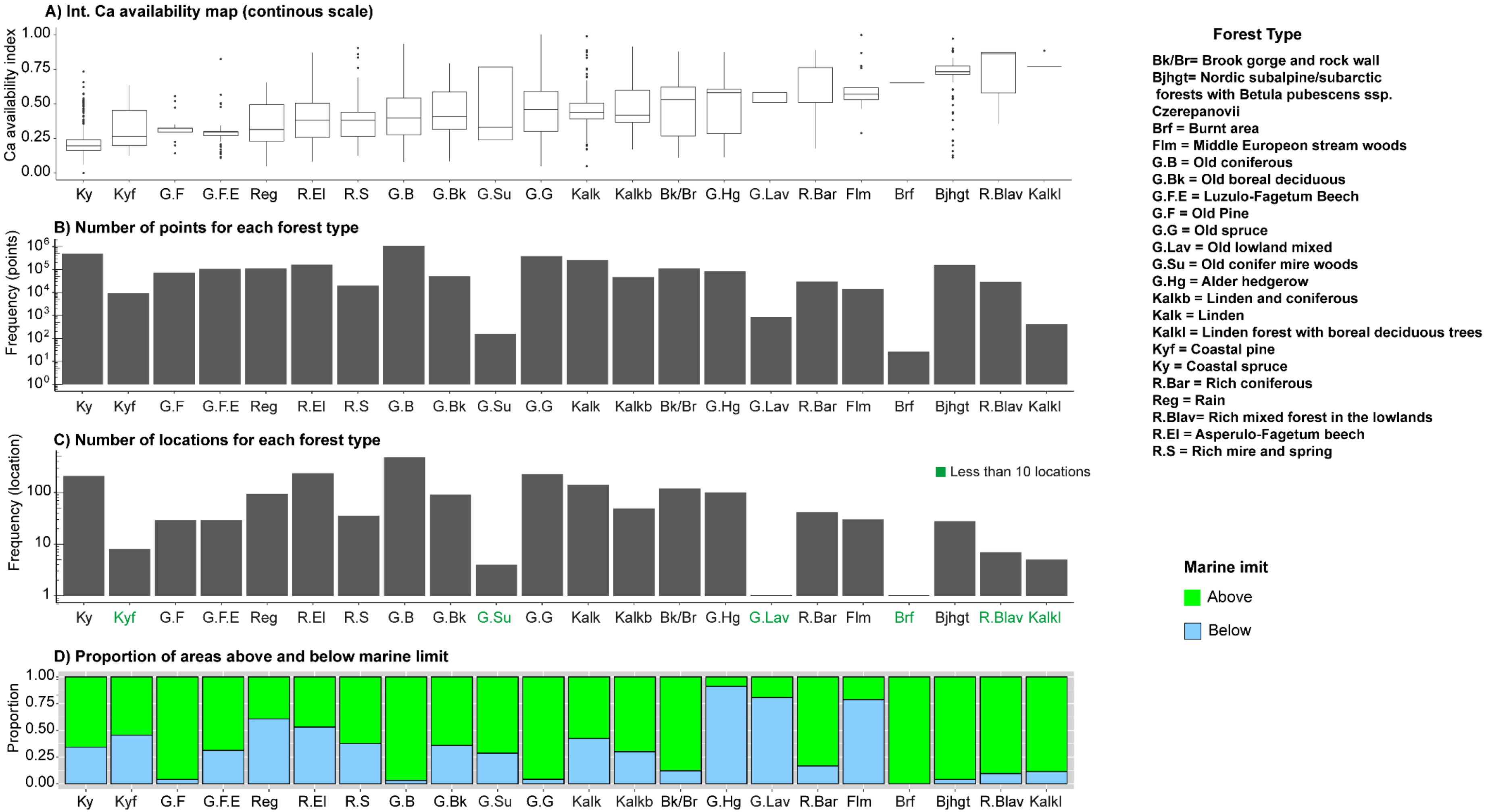

Figure 17. A) Integrated calcium availability index results by forest type (continuous scale). B) Number of points calculated from the raster maps for each forest type. C) Number of localities where the distinct forest types are recognized (in-situ observations). D) Percent of samples obtained in areas above (AML) and below marine (BML) limit.

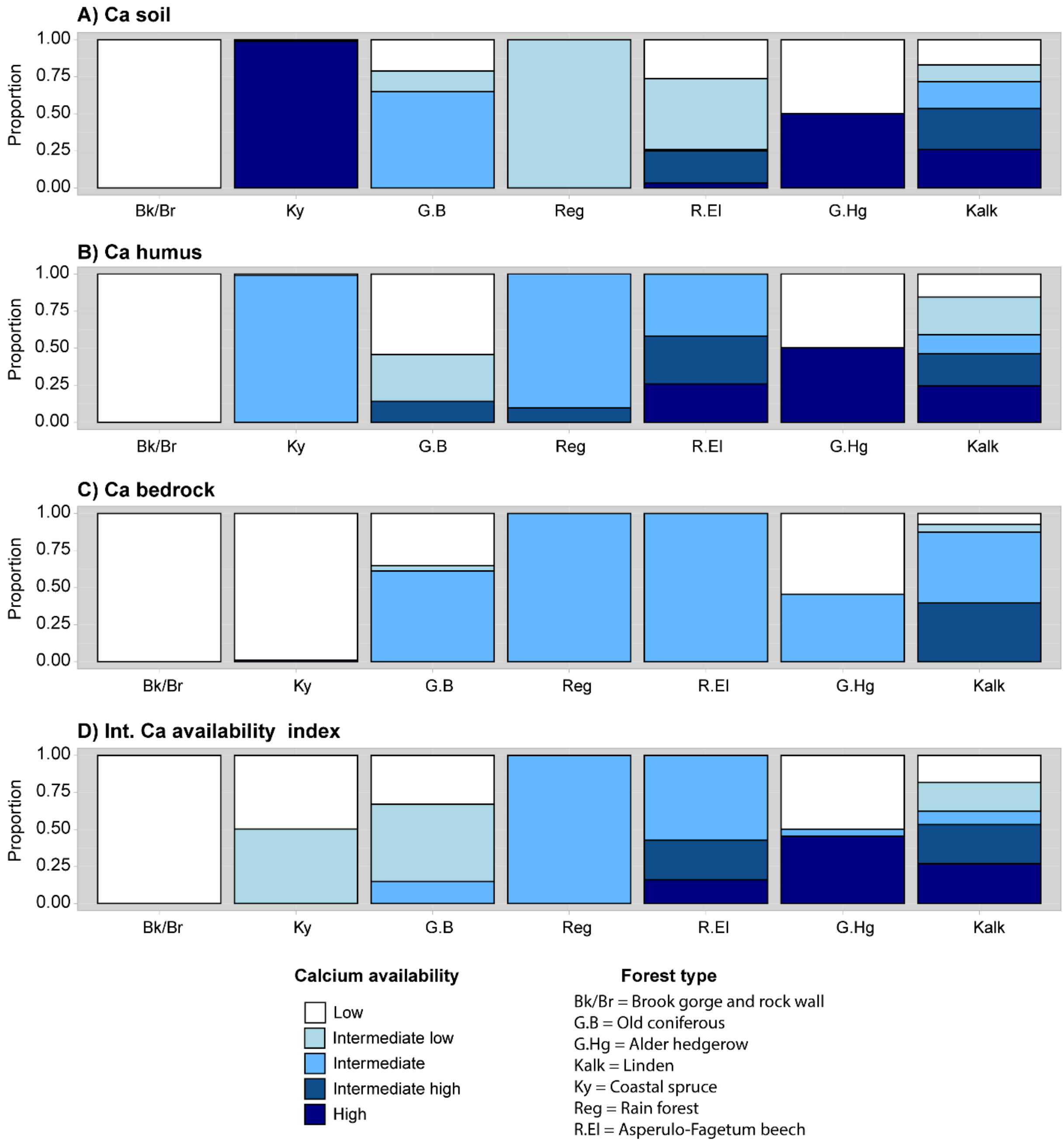

Figure 18. Steinkjer survey. Stacked bar plots showing the proportions for each forest type in terms of their occurrence in the normalized soil (A), humus (B), bedrock (C) and integrated (D) calcium availability maps.

Interesting enough, the coastal spruce forest type (kystgranskog) displays intermediate high and high calcium availability values for humus and soil respectively, but very low values for calcium in bedrock (**Fig. 18A, B**). When plotted in the ICA map, this forest type locates in areas with intermediate low to low calcium budgets. The lack of spatial correlation between bedrock and its overlying loose material (humus and soil) calcium budgets is likely due to the regional scale of the bedrock study. Consequently, local changes in the calcium availability of a particular lithology will be underestimated.

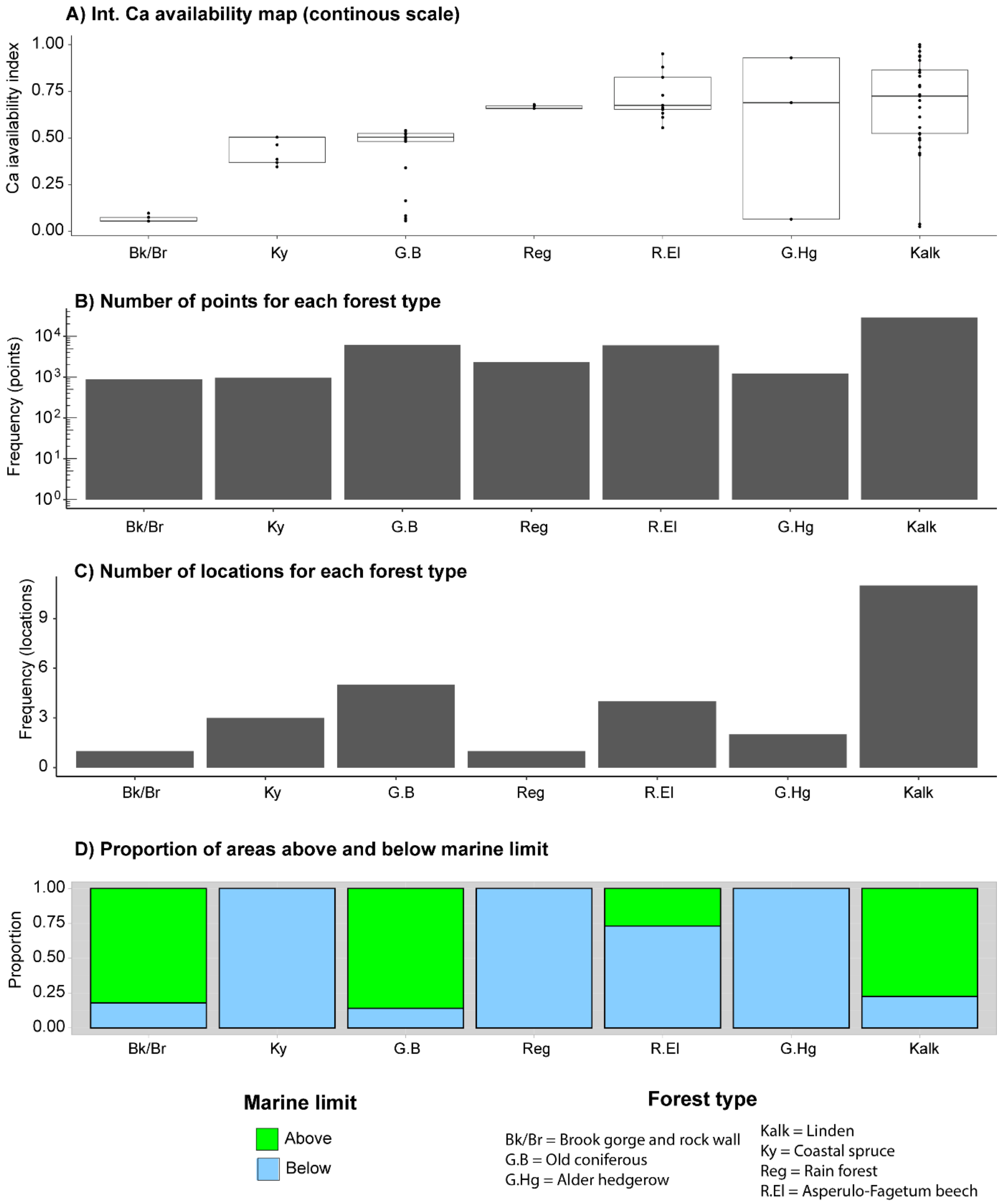

Figure 19. Steinkjer survey. A) Integrated calcium availability index results by forest type (continuous scale). B) Number of points calculated from the raster maps for each forest type. C) Number of localities where the distinct forest types are recognized (in-situ observations). D) Percent of samples obtained in areas above (AML) and below marine (BML) limit.

7. Future work

Further work regarding the integration and spatial correlation of calcium in different media with natural species (i.e., forest types) should be focused on: i) the automatization of workflows, ii) collection/acquisition of relevant field- and remote sensing-driven data, and iii) implementation of multivariate analysis (i.e., unsupervised, and supervised machine-learning).

Automatization of workflows. To advance towards a national scale application of this methodology, it is imperative that all data processing (and updating) involving e.g., generation of multiple raster and point maps, elaboration of spatial joins and statistical plots (e.g., stacked bar and box-whiskers) is automatized and completely integrated with a GIS platform. Automatization of these processes can be carried out using the open-source Python programming platform fully integrated with the ArcGIS Pro and QGIS software packages. We favour the latter's usage due to its open-source nature, and its increased use in the research community, principally by early-career scientists, consultants, and students.

Collection/acquisition of relevant field and remote sensing data. The Trøndelag county was selected for the availability of multiple media geochemical databases. However, this coverage is not extended to the rest of the country. In particular, humus sampling is limited to a few counties in Norway. Currently, NGU is conducting a regional soil and humus geochemical survey in middle and southern Norway, but the northern portion is devoid of such information. A humus survey(s) should be therefore carried out in these areas. Collection of other parameters such as geophysical (e.g., radiometric, magnetic and hyperspectral data), topographical, and atmospheric data (e.g., precipitation, temperature) may also aid to better define spatial correlations among calcium sources (bedrock, soil, humus and water), topography, climatic conditions and the dominance of certain natural species in particular areas. It is of special interest to implement methodologies that allow remote sensing data to be used as a proxy for natural species (e.i., forest types) in a way that it has a coverage comparable to that of the other media layers used for the ICA.

Implementation of multivariate analysis (i.e., unsupervised, and supervised machine-learning). Unsupervised machine-learning (e.g., principal component, cluster analyses) should be first used to identify statistical correlations among the geo- and atmospheric parameters mentioned above and their correlation (if any) with forest types. Once these correlations are identified and the statistical relevance of each parameter assessed, appropriate training datasets should be elaborated to permit supervised learning (e.g., random forest, neural networks, partial square linear discriminant analysis).

8. Conclusions

- This present study has successfully identified lime (i.e., calcium concentration) sources in loose material (soil and humus) and water (stream water) and designed a methodology for elaborating an integrated calcium availability map.

- Data from the northern Trøndelag area indicates that calcium availability in areas below and above the marine limit are statistically comparable.

- In both regional and local scale surveys, the spatial correlation between calcium in humus and in bedrock is greater than that of calcium in soil and in bedrock, indicating that for some elements, humus may be a better proxy to characterize the underlying lithologies. This may have important implications e.g., mineral exploration surveys and environmental assessments.

- Within the limitations of the approach, this study identified forest types that commonly occur in areas with low and high calcium availability. Validation of our methodology is given by the fact that in both surveys (regional and local), lime-rich forest types (Lf, LCf and LCBf) were mainly contained in areas having intermediate to high calcium availability values in different media and the ICA.

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