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Vegetation mapping of Svalbard utilising Landsat TM/ETM+ data

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ABSTRACT. The overall objective of this paper is to present and discuss the most recently developed vegetation map for Svalbard, Arctic Norway. The map is based on satellite images in which several Landsat TM/ETM+ images were processed through six operational stages involving: (1) automatic image classification, (2) spectral similarity analysis, (3) generation of classified image mosaics, (4) ancillary data analysis, (5) contextual correction, and (6) standardisation of the final map products. The developed map is differentiated into 18 map units interpreted from 37 spectral classes. Among the 18 units separated, six of the units comprise rivers, lakes and inland waters, glaciers, as well as non- to sparsely vegetated areas. The map unit 7 is a result of shadow effects and different types of distortions in the satellite image. The vegetation of the remaining eleven units varies from dense marshes and moss tundra communities to sparsely vegetated polar deserts and moist gravel snowbeds. The accuracy of the map is evaluated in areas were access to traditional maps have been available. The vegetation density and fertility is reflected in computed NDVI values. The map product is in digital format, which gives the opportunity to produce maps in different scales. A map sheet portraying the entire archipelago is one of the main products from this study, produced at a scale of 1:500,000.

Introduction

At present attention on the Arctic areas is highly focused due to the continuing global climate change debate. The predicted rise in air temperature for northern latitudes will, if they come to pass, cause changes in plant and vegetation distribution and diminish the extent of permafrost in terrestrial systems. Parallel processes in marine systems are widely used to explain the negative trend in summer time sea ice extent. These changes will, in turn, have feedback effects on the global climate system. In order to understand and mitigate the consequences of the predicted changes a sound understanding of all northern ecosystems is needed. For terrestrial systems information on the occurrence and content of different vegetation communities is important in order to evaluate the limiting factors for plant growth. In this context both conventional and satellite based vegetation maps play an important role.

The Svalbard archipelago is located in the high Arctic. Due to the remote location access to information on vegetation is highly varied within the region. For some areas detailed recordings of plants and community types are available, while others have hardly been visited by any botanists. At a general level most efforts have been devoted to recording the occurrence and distribution of different plant taxa in the archipelago. *The flora of Spitsbergen*, published by Rønning (1996), summarises large parts of the work being done within this research area.

Regarding research on vegetation communities, Rønning (1965) published a survey of all community types characterised by *Dryas octopetala* (mountain avens) on Svalbard. In the years since then different community types within the archipelago have been recorded by several authors. In a survey of plant associations and alliances on Svalbard, given by Elvebakk (1994), all the important basic literature describing vegetation units on Svalbard was reviewed.

Several attempts have been made to derive vegetation maps for Svalbard. At regional level Brattbakk (1986a) separated the area into two overall regions, the mid- and high Arctic, with a further division of both regions into subgroups of dominant species. A later proposal presented by Elvebakk (1997), suggested an overall division into three bioclimatic regions, the middle arctic tundra zone (MATZ), the northern arctic tundra zone (NATZ), and the arctic polar desert zone (APDZ). At local scales several conventional maps have been produced as a part of general research activity on Svalbard. During the research project 'Man and biosphere', the area of Brøgger Peninsula was covered by 8 vegetation maps at a scale of 1:10,000 (Brattbakk 1986b). Corresponding maps were produced for the areas of Adventdalen, Franken Peninsula, Lågnesflya, Reinsdyrflya and Lapponia Peninsula. In these maps the vegetation units were arranged into ecological series (heath, meadow and marsh/mire) with a further differentiation of the vegetation cover along a density gradient.

In the years after this, additional areas have been mapped, both using conventional methods (Gipsdalen, Edgeøya) and by the use of satellite images (Spjelkavik 1995; Nilsen and others 1999a, 1999b). In Gipsdalen valley Elven and others (1990) developed a map (1:25,000) in which the main principles from the series approach were adapted with a further differentiation in major ecological habitats. Here satellite images were used as reference data and compared to the conventional map produced. For Edgeøya a landscape ecology map, at a scale of 1:200,000, was produced by the Dutch Spitsbergen expedition (1968–1969) and published by Zonneveld and others (2004). The most recently produced vegetation map of the entire Svalbard archipelago was published by Elvebakk (2005). In this map the dominant vegetation types on Svalbard are differentiated into 15 map units. The units further combine different types of information associated with summer temperature, soil chemistry, hydrology, manuring effects, aridity and substrate instability.

The overall objective of this paper is to present and discuss the most recent vegetation map produced for Svalbard. The map covers the entire archipelago apart from some of the easternmost islands (Kvitøya, Kong Karls Land, Svenskeøya, Hopen). The map product is produced from several Landsat TM/ETM+ images, most of them acquired around the year 2000. All images are classified using the k-means classification algorithm and compiled into a seamless, generalised and consistent map product. The final map contains 18 map units. The accuracy of the developed map is evaluated in areas were access to traditional maps have been available. The map product is in digital format, which gives the opportunity of producing maps at different scales. A map sheet portraying the entire archipelago is produced at scale of 1:500,000. A sub-section from the map database, portraying Nordenskiöld Land, is produced at a scale 1:100,000. By extracting different class layers from the map database, different types of thematic maps can be produced. The produced map product is as a branch of the larger management project on Svalbard performed by the Norwegian Polar Institute 'The environmental surveillance of Svalbard and Jan Mayen' (MOSJ http://mosj.npolar.no/en/index.html).

Material and methods

The study area

The archipelago of Svalbard is located in the Arctic part of Norway extending roughly from 74 to 81°N, and from 10 to 35°E (Fig. 1). The archipelago consists of more than 500 islands in which those of Spitsbergen, Nordaustlandet, Edgeøya and Barentsøya are the largest. Large parts of the area are mountainous with summits above 1500 m. The coastal areas in north and west are deeply indented by fjords. Glaciers are the most characteristic landscape feature on the islands covering more than 60% of the land area.

Despite its northern location, Svalbard has a relatively mild climate. On the archipelago the climate shifts from typically humid, oceanic areas in the west to colder and drier climate conditions in other parts of the archipelago. This shift is mainly explained by the gulf stream affecting the western areas, while cold northern sea currents affect the northern and eastern regions. Along the western coast, temperatures in July are usually inside the range of 1–10° C, with an average of 4.8° C at Isfjord Radio. In the fjord zone the summer temperatures are a little elevated showing 5.9° C as the July average for Longyearbyen. In winter the mean temperatures are generally low, with an average of –12.4° C in February at Isfjord Radio. In the fjord zone the winter temperature is even lower expressed by an average in February of –16.2° C for Longyearbyen. The amount of

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Fig. 1. Svalbard archipelago is located in the Arctic parts of Norway (74–81° N, 10–35° E). The two test sites used in map verification is given by squares.

precipitation on the entire archipelago is generally low with averages along the western coast between 400–500 mm. The fjord zone is extremely dry with annual means for Longyearbyen showing only 190 mm. The geology of Svalbard is highly varied and all geological periods are represented.

The map production scheme

When creating vegetation maps over large areas using satellite data, several operational tasks have to be put together to produce a full map production scheme as displayed in Fig. 2 (Johansen and others 2009).

The process of working out vegetation maps can be separated into six operational stages. The initial stage (1) involves selection and classification of a pre-selected 'master' image. The classification was performed using the unsupervised k-means algorithm (Maxwell 1976; Niblack 1986). Next the classified product is analysed with respect to spectral similarity and separability in order to decide the ultimate number of classes in the first-order classified product. (2) After stating the class number within the master image, the neighbouring images were classified using the k-means classification algorithm and added into the initial classified master scene. During the image mosaicing process the 'master-slave mosaicing method' was conducted (Homer and others 1997: Vogelmann and others 1998). Regions of overlap between the 'master' scene and adjacent 'slave' scenes are analysed with respect to class comparability. Based on this comparison equal class sequences were worked out for both the 'master' and the 'slave' image. Once a similar class sequence was stated for both images, the images were merged together constituting a new 'master' image. Classes from the 'slave' image which do not correspond to any of the classes in the 'master' scene were added as new classes in the class sequence. (3) The process of classifying new images in order to create new master images, continues until the entire study area is portrayed as a seamless mosaic of pre-classified images. (4) In this stage different types of ancillary data are prepared for analysis and related to the seamless pre-classified map. (5) The fifth stage involves formulation of decision rules for splitting or merging of classes in a contextual correction process. (6) Finally the end product is standardised to a vegetation scheme valid for the study area.

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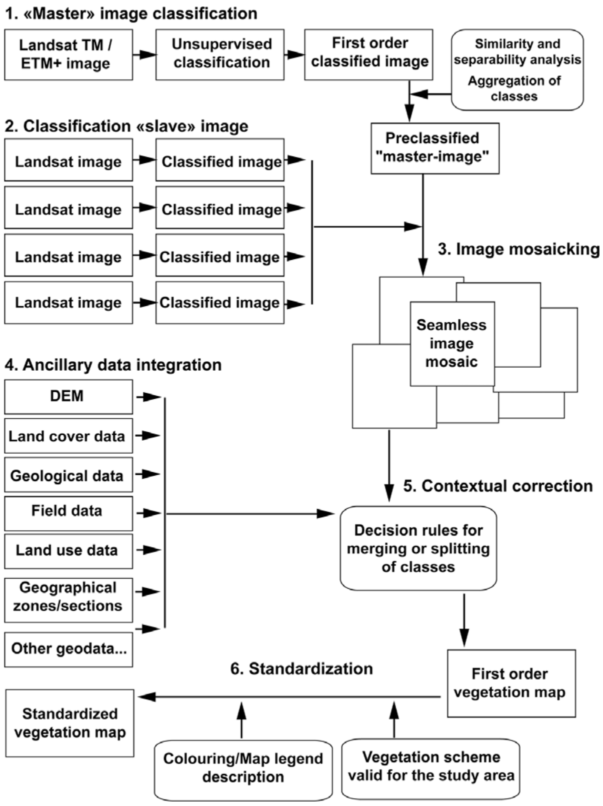

Fig. 2. Process flow chart outlining the six different steps in the map production process.

Table 1. Satellite images used in the study.

No	Satellite	Sensor	Track/ frame	Date	Sun angle
1	Landsat 5	TM	221/3	27.07.1987	27.0
2	Landsat 5	TM	218/2	16.08.1998	24.7
3	Landsat 5	TM	218/3	16.08.1998	24.7
4	Landsat 7	ETM+	214/3	17.08.2000	24.8
5	Landsat 7	ETM+	214/4	17.08.2000	24.8
6	Landsat 7	ETM+	208/4	12.07.2002	33.6
7	Landsat 7	ETM+	208/5	12.07.2002	34.9
8	Landsat 7	ETM+	210/3	10.07.2002	32.6
9	Landsat 7	ETM+	212/5	22.06.2002	36.3
10	Landsat 7	ETM+	215/2	10.07.2001	31.3
11	Landsat 7	ETM+	215/3	13.07.2002	32.2

Available data layers

The satellite data used in this study consist of a total number of 11 Landsat TM/ETM+ images as summarised in Table 1. Five of the images represent a core centre of image collection, covering most of the central and northern parts of the island of Spitsbergen. The images 208/4–5 cover the eastern and southern parts of the archipelago, while the remaining images are used to correct for cloud distortions. The image 214/4, acquired on 17 August 2000 is selected as the 'master' image in the map production process.

The images collected were geo-referenced to the UTM map format, zone 33, WGS84, using the control point correction method with a root-mean square error of less than one pixel. The image processing was performed using ENVI image processing software. The geographic information analyses were performed on ArcGis - Geographical Information System. In the map production process different types of ancillary data are needed in the contextual correction of the spectral only classified product. Ancillary data sources used in this study comprise digital elevation models, digital topographic maps containing separate cover layers of river plains, deltas, glaciers and ocean/inland waters. From the digital elevation model different maps describing different aspects of the terrains are compiled.

Field study and map evaluation

Three different approaches were taken in order to evaluate the quality of the final map product. These were the collection of field data, the comparison to conventional maps and 'point evaluation' within areas extensively recorded through former expeditions.

During the field study large parts of the archipelago were visited by helicopter. Prior to the flight preclassified images were worked out and used to search out areas with characteristic vegetation types or anomalies in pre-classified images. During the flights 25 sites were visited and documented by a large number of oblique photographs. The geographical position of all visited sites was recorded using GPS. The helicopter flights were steered in three directions; day 1: - to northwestern Spitsbergen; day 2: - to the islands of Edgeøya and Barentsøya and to the northeastern parts of Spitsbergen; day 3; - to western and southern Spitsbergen.

In the second evaluation approach subsections from conventional maps were compared with the satellite based product. The areas of Brøgger Peninsula and Gipsdalen valley were selected for this comparison. On Brøgger Peninsula 8 maps are available and displayed at a scale of 1:10,000 (Brattbakk 1981). A subsection from the northernmost tip of the peninsula is selected for a visual map comparison in this study. For the Gipsdalen valley (Elven and others 1990) corresponding maps were available, at a scale of 1:25,000. Here a statistical based comparison was performed using methods in Landis and Koch (1977) and van Genderen and others (1978).

The third type of map evaluation performed in this project, deals with areas being extensively recorded in the field through earlier projects. 108 ground sites representing 20 different areas were selected and evaluated with respect to class accuracy.

The map product

Classification and reflectance properties

The vegetation map developed in this project is displayed in Fig. 3. The final map product is differentiated into 18 vegetation units. The map units are described below.

In the initial clustering the 'master' image was separated into 32 spectral classes (Johansen and others 2009; Speed and others 2009). The classification was performed using the unsupervised k-means algorithm (Maxwell 1976; Niblack 1986). The spectral similarity between classes was computed based on Euclidian

Fig. 3. Vegetation map of Svalbard, originally at scale 1:500 000. The map is differentiated into 37 spectral classes and further aggregated into 18 map units. The descriptions of the map units are given in section 3.2.

distance and further aggregated into a dendrogram (Fig. 4). In this aggregation of classes both the 'unweighted group average method' (UPGMA) (Sneath and Sokal 1973) and Ward's method (Ward 1963) were conducted. The dendrogram reflects the hierarchical relationship between classes (Gauch and Whittaker 1981) and states the class separation at different interpretation levels. The information extracted from the dendrogram serves as the main guideline in the first order interpretation of separated classes.

By inspecting the dendrogram, the first interpretation level separates the glaciers (32) from the remaining material (A'). In the second level (B') the classes 29 and 31 are separated associated to non-vegetated gravel areas. The third level (C) displays the distinction between dry and wet community types. Here the branch C aggregates a wide range of wet classes ranging from open water, via wet seashore and river banks, to melt-water ponds on the glaciers. The three classes (5, 7, 9) associated with shade areas are included in this branch. The vegetated areas aggregated in branch C' are further differentiated into exposed community types (D') and vegetation communities with established vegetation covers (D). During the classification and merging of images neighbour to the master scene, five new classes were created. By this, the final pre-classified product contains a total number of 37 spectral classes.

The differences in reflectance properties between classes constitute the basis for class separations. For vegetation communities this distinction is made by the community type itself and by the stand growing conditions. Densely vegetated communities on dry substrate are characterised by chlorophyll absorption in the visible red (TM3) and high reflectance values in the near-infrared (NIR) wavelengths. Water is characterised by reflection in the visible part of the spectrum, particularly in the blue channel (TM1), and absorption in the mid-infrared (MIR). For vegetated areas on wet subsoil the reflectance

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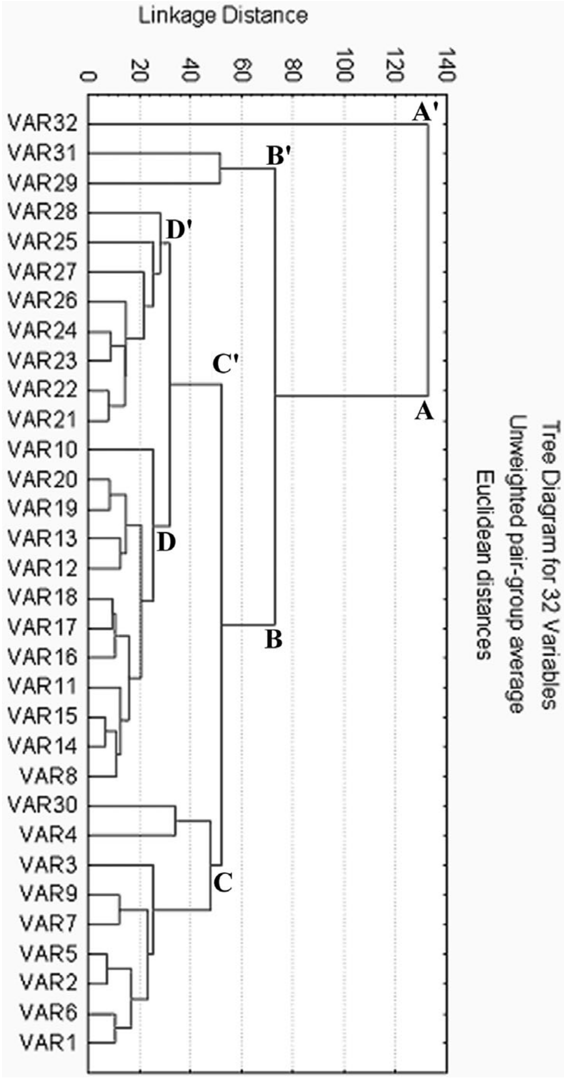

Fig. 4. Dendrogram displaying the spectral relationship between classes for the master image, Landsat ETM+, 214/4.

values in the TM5/7 channels are generally reduced, but vary with the water content in the ground and with water stored in the plant tissue. The reflectance pattern for bare soil increases with increasing wavelengths.

Experience from earlier mapping projects has proved that many of the classes separated using unsupervised classification methods are highly comparable with respect to vegetation cover and content. This is particularly the case for Arctic areas, where sparse vegetation coverage characterises large parts of the ground. One of the main challenges in the interpretation of the pre-classified map is to distinguish non-vegetated classes from areas containing any type of vegetation and to aggregate initially separated classes into an appropriate number in the final map product. Computed JM-distance values (Niblack 1986) were used to evaluate the end number of classes, while NDVI values (Table 2) serve as an important source of information to separate dense, fertile classes from exposed areas.

Fig. 5. The Paula glacier in the inner parts of Van Mijenfjorden (Photo: BJ - 2008).

By inspecting the hierarchy of the dendrogram, the computed JM-distance and the NDVI values, the number of classes was reduced from the initial 37 to 18 map units by class aggregation. In the final map the distinction between sea/ocean, inland water and broad rivers is established by use of ancillary topographic maps. The coverage of glaciers is established by aggregating the classes 4, 6 and 32 in the pre-classified product. The reflectance properties for the final 18 map units are summarised in Table 2. The aggregation of classes and the class interpretation of the pre-classified product is given in the referred table.

Map legend descriptions

In this section the final 18 map units are described with reference to the classes in the pre-classified image. The initial 7 units are mainly free of any vegetation cover, while the remaining 11 units are generally vegetated. The vegetation cover within the units varies from sparsely vegetated gravel community types, to dense marshes and moss tundra vegetation.

1. Sea, oceans (1). Bordering oceans to the archipelago are the Barents Sea (E), the Polar Sea (N) and the North Atlantic (S and W).
2. Inland water (2). Inland water is generally sparsely represented on Svalbard. The largest lakes and inland waters are found in the north, often bounding the glaciers.
3. Broad flooding rivers (3). The extent of rivers varies highly during the summer period from large flooding rivers in the melting period to a smaller extent in the late summer and autumn period.
4. Glaciers (4,6,32). The glaciers constitute the prevailing landscape on Svalbard (Fig. 5). To some extent late snowbeds are aggregated in this map unit.
5. Wet, non-vegetated to sparsely vegetated flats, beaches, slopes and river fans (8,16,30). The unit integrates different types of non- to sparsely vegetated areas on moist to wet subsoil. The classes constituting this unit are represented both in lowland and in the mountain areas. Sterile, loamy flats associated to flooding rivers, river fan mosaic, seashores and recent moraines bounding the glaciers are the main landscape elements within the unit.

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Table 2. The table summarizes the final class number, the aggregation of classes, reflectance properties and the NDVI values for the aggregated classes and a first order class interpretation.

Clusters & classes		Landsat TM/ETM+ channels							
		TM1	TM2	TM3	TM4	TM5	TM7	NDVI	Interpretation and labelling of classes
1	1	40,95	30,19	27,63	26,08	17,59	14,77	−0,03	Sea, ocean
2	2	35,31	22,43	17,06	14,85	10,21	9,46	−0,07	Inland water
3	3	53,73	37,83	34,38	29,69	12,90	11,61	−0,07	Broad flooding rivers
4	4,6,32	115,11	100,46	109,92	97,22	15,02	13,31	−0,06	Glaciers, snow
5	8,16,30	43,73	34,25	35,37	39,23	40,64	34,23	0,05	Wet, non-vegetated flats, beaches, slopes
6	28,29,31	54,79	48,37	55,04	64,55	79,26	66,16	0,08	Dry, non-vegetated to sparsely vegetated
7	5,7,9	37,00	25,79	23,66	25,32	22,29	18,64	0,03	Shadows and shade effects
8	14,15,33	35,62	25,69	24,70	37,32	44,43	31,46	0,20	Pioneer vegetation, sparsely vegetated
9	11,34,35	34,16	24,27	22,65	39,76	35,99	23,73	0,27	Moderate snowbed and snowflush areas
10	10,36	32,59	23,28	21,09	50,70	31,67	18,79	0,41	Swamp and wet moss tundra communities
11	13	33,01	24,83	23,09	59,50	47,87	27,25	0,44	Mires and marsh tundra communities
12	12	33,39	24,30	22,84	47,31	47,29	29,09	0,35	Moist tussock tundra
13	17,22	39,00	29,59	29,99	44,52	54,90	39,86	0,20	Exposed Dryas tundra
14	18,21,37	35,98	26,19	25,57	41,13	56,96	38,57	0,23	Established Dryas tundra communities
15	19,20	34,12	25,15	24,12	50,27	57,41	34,74	0,35	Arctic meadow communities
16	25	35,43	27,40	27,08	61,22	68,49	41,30	0,39	Exposed graminoid communities
17	23,24	42,25	33,42	34,97	41,15	53,37	44,70	0,08	Gravel barren communities
18	26,27	45,88	38,15	41,40	48,65	61,47	51,27	0,08	Gravel snowbed communities

To some extent *Deschampsia alpina* stands are found in this unit.

6. Dry, non-vegetated to sparsely vegetated barrens, slopes and ridges (28,29,31). The general definition of the class is dry, non-vegetated areas both in lowland and in the mountains. The main occurrence of the unit is in the mountains associated to gravel barrens, exposed rocks, block fields and talus slopes (Fig. 6). In the lowland bare rocks, exposed ridges, gravel flats and river fans constitute the class. To some extent the most exposed parts of the Arctic polar desert zone are included in the unit.
7. Shadows and shade effects (5,7,9). Areas affected by shadows are associated with landscape with varied topography. This situation is found in large areas on Svalbard. Low sun angles, due to northern latitudes further reinforce the shadow distortions. Classes mostly affected by shadow distortions are collected in this group; located mostly in northern hill slopes. To some extent different types of wet vegetation communities are within the class, characterised by low reflection in all channels.
8. Pioneer-vegetation (14,15,33). In general pioneer vegetation comprises vegetation communities strongly affected by erosion and accumulation, both during times of flooding and by silt transport during the melting season. The map unit includes perennial mud flats, irrigating hill slopes, partly established river fans and salt marsh vegetation. In mountain areas some late snowbed communities constitute the class, characterised by few vascular species and mosses.
9. Moderate snowbed and snowflush communities (11,34,35) are found in areas with snow protection during winter. The snow protects against the extensive arctic cold and desiccation. It further serves as a moisture source in early summer, and as a determinant for the duration of the growing season. Moderate snowbeds vary highly in composition from moss rich communities, to tussock flats, often with ponds of open water. They are most commonly developed in the lower parts of hill slopes and in depressions in the mountains and constitute large areas along the coast, in the north and in the eastern parts of the archipelago.
10. Swamp and wet moss tundra (10,36). In general, swamp vegetation is located in areas with stagnate, standing water, while wet moss tundra communities are developed in gently sloping terrain, but still with the ground water just below the ground surface. Mosses characterise both community types. Swamp communities are characterised by single species stands of distinctly arctic species (*Arctophila fulva*). Wet moss tundra shows a more varied species composition, characterised by mosses and a higher number of vascular plants (*Carex subsphatacea*, *Eriophorum triste*, *Dupontia psilosantha*, *Ranunculus hyperboreus*).

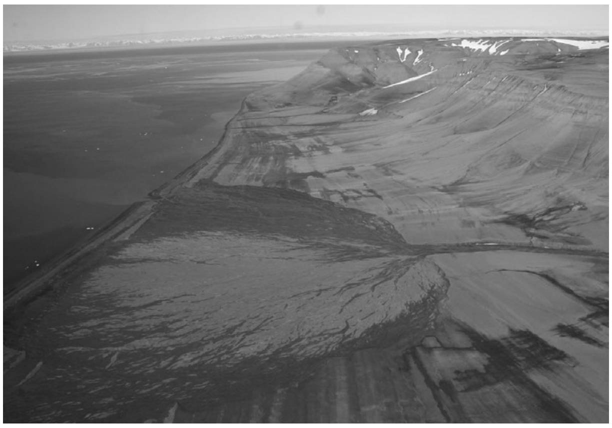

Fig. 6. Sparsely vegetated gravel slopes, ridges and seashores on Edgeøya (Photo: BJ- 2008).

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Fig. 7. Hygrophilous marshes with *Eriophorum scheuzeri*, *E. triste* and *Equisetum arvense* as common species. In the background, drier stands of *Dupontia fisheri*. Adventdalen (Photo: BJ-2010).

Fig. 8. Established *Dryas* tundra with *Cassiope tetragona* as one of the characterising species. Vårfluesjøen. (Photo: G. Arnesen).

To some extent luxuriant bird manured areas are included here. The distribution is restricted to the lowland.

11. Mires and wet marsh tundra (13). These community types are most often developed in sloping terrain constituting grass-, sedge- and herb-rich communities. The water status varies from typically moist stands of mosses, grass and sedges (*Dupontia pelligera*, *Eriophorum scheuchzeri*, *Carex parallela*, *C. saxatilis*) to drier, shallow marshes with a more scantily developed moss layer (Fig. 7). The communities types constituting this map unit are highly productive and of high importance as pastures for reindeer and geese.
12. Moist tussock tundra (12). Developed in areas with moderate snow cover during winter. Most often developed in the lower parts of hill slopes, on established river-fans and in small depressions. The vegetation layer is open to partly closed, often characterised with by small tussocks. The overall formation is a mixture of heather and moderate snowbed species. Characteristic species are *Salix polaris*, *Dryas*, *Equisetum arvense*, *Saxifraga oppositifolia* and *Silene acaulis*. The moss layer is generally moderately developed.
13. Exposed *Dryas* tundra (17,22,37). Community types developed on dry, exposed gravelly ridges, terraces, beach ridges and river fans. The vegetation cover is discontinuous with sparse snow protection during winter. The characterising species are *Carex rupestris*, *C. nardina* and *Saxifraga oppositifolia*, combined with scattered *Dryas*. In some areas lichens are of rather great importance. The community type is widespread over large areas in the MATZ and NATZ regions.
14. Established *Dryas* tundra (18,21). In areas with a more heavy snow cover, established *Dryas* tundra is developed. These communities are developed on terraces, hill slopes and small depressions in the terrain. The most common variant is poor in species, while others may contain herbs, sedges and lichens. In depressions and where less drained sites dominate, community types characterised by mosses in combination with *Cassiope tetragona* (Fig. 8) are developed. On coastal plains *Saxifraga oppositifolia* communities, partly with lichens, may constitute large areas. In the mountain areas, as well as in most northern and easternmost parts of the archipelago *Dryas* stands with *Papaver dahlianum* are common.
15. Arctic meadows (19,20). Luxuriant vegetation communities characterised by grasses and forbs combined with a high species number. Associated to warm south- and southwest facing slopes with some supply of water during the growing season. The community types are mainly distributed in the MATZ bioclimatic zone constituting largest areas on Dickson Land, and in the valleys of the fjord zone. To some extent luxuriant bird cliff vegetation, established densely vegetated river fans and the drier parts of *Dupontia* meadows are included in this map unit.
16. Exposed graminoid communities (25). The map unit comprises open, extremely dry communities characterised by grass, sedge and rush species. Often found in upper parts of steep hillsides, on ridges and shoulders of mountain plateaus. To some extent lichens are developed. The general picture of this map unit is open grass and sedge fields, limestone cliffs and high arctic steppe vegetation characterised by *Potentilla pulchella*, *Poa abbreviata* and *Puccinellia angustata*. The unit is mainly represented in the fjord zone, and may serve as important as winter ranges for reindeer.
17. Gravel barren communities (23,24) constitute non- to sparsely vegetated gravel-, boulders- and block fields, often characterised by large polygons (Fig. 9). Species like *Papaver dahlianum*, *Saxifraga oppositifolia, Luzula nivalis* and *Luzula confusa* are most common among vascular plants, while lichens may be abundant in areas with a stronger substrate stability. Gravel barren communities are often denoted polar deserts and mainly associated to the mountain regions and to the northern and eastern islands of Svalbard.
18. Gravel snowbeds (26,27) represent late snowbed and snow flush communities in the Arctic polar desert zone. The vegetation cover is open with scattered plants of *Cerastium regelii* and *Phippsia algida* as most common. The bryophyte layer may be densely developed, combined

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Fig. 9. Gravel polar desert characterized by *Papaver* and *Luzula* species (Photo: B.E. Sandbakk).

with liverworts. The main distribution on Svalbard is in the mountains and on the eastern islands.

Map verifications

The conventional maps used during the map verification are selected from two different geographical regions of Svalbard, the Brøgger Peninsula and the Gipsdalen valley, respectively. The map of Brøgger Peninsula is located in the NATZ bioclimatic zone characterised by open to established *Dryas* communities, moss tundra and exposed ridge communities. The Gipsdalen site is located to the MATZ zone, showing more varied vegetation composition comprising *Dryas* communities, swamps and wetlands, moist marshes and river fans in stabile and instable stages.

Brøgger peninsula test site

The flora and vegetation on Brøgger Peninsula are well known and have been investigated by several botanists (Rønning 1965; Spjelkavik 1995; Nilsen and others 1999a, 1999b). The subsection presented in Fig. 10, shows the northernmost parts of the peninsula. The conventional map, created by Brattbakk (1981), differentiates the area into three main types of vegetation; the heather communities, the meadows, the marshes and wetlands. A further distinction is related to the vegetation density.

In the conventional map, exposed flats and ridges characterised by *Saxifraga oppositifolia*, combined with lichens, constitute the prevailing community type within the area. Today the lichen carpets are depleted due to heavy grazing by reindeer for the past few decades (Ozasz-Albrigtsen 1999). A second type of ridge communities within the area is characterised by the *Dryas*, combined with *Carex rupestris* and *C. nardina*. These communities are associated with areas with stony subsoil and solid rocks. The northernmost tip of the subsection is mapped as a complex of *Deschampsia alpina* snowbeds combined with wetlands of *Dupintia fisherii* and *Arctophila fulva*. Outside the map subsection, in areas more to the southwest, fertile heather and grass rich communities are recorded. The fertility of these areas is explained as being due to manurial effects from local bird-cliffs.

The satellite based map gives an equal overall expression of the vegetation formations within the selected sub-section. The most exposed flats and ridges are in this map aggregated into the unit no 6, described as 'non-vegetated barrens, slopes and ridges'. In the spectral classification this unit is differentiated into three classes with two of them recorded in this area. The class no 31 is interpreted as non-vegetated gravel mainly located on ridge crests, while class no 28 may have a slight vegetation cover and some snow protection during winter. The communities are interpreted more exposed compared to the conventional map. This interpretation is highly relevant for today's description of the area, in which the reindeer grazing has left large areas free of any vegetation. The more dense heather tundra communities show a high degree of correspondence, while some of the snowbed stands in the conventional map are recorded as a mixture of moist heather tundra and snowbeds in the satellite map. Wetland areas in both map products show a high degree of correspondence.

Gipsdalen valley test site

The flora and vegetation of Gipsdalen valley was extensively recorded during the years 1987–1989 by botanists from the University of Tromsø. The main results from these expeditions were summarised by Elven and others (1990), and they presented vegetation maps covering most of the lowland areas of the valley. The vegetation of Gipsdalen is influenced by the calcareous substrate, resulting in a wide distribution of open vegetation types and more restricted distribution of closed vegetation. The species content in many habitats differs from what is usually found in other areas of the interior fjord zone. Large parts of the valley floor are characterised by gravelly or loamy sedimentation flats, partly sterile, partly sparsely vegetated. The maps and image subsections presented in Fig. 11 display parts of the Gipsdalen valley test site. The conventional map is viewed to the left, the satellite based map in the middle and a 3-band Landsat image (ch421) to the right.

The heather tundra communities characterised by *Dryas octopetala* constitute the prevailing vegetation type within the area, and are mainly associated with the hill slopes, established river fans and stable moraine subsoil. In the conventional map a distinction is made between exposed (pale yellow) and established (orange) types of *Dryas* communities. In the conventional map wet moss tundra and moist marshes show a restricted distribution in Gipsdalen, except from a large and varied area found inside some raised beach ridges at a distance of 2 km from the sea shore, on the eastern side of the river (green). Several sub-groups of wetlands are differentiated in this area based on dominating grass, sedge and moss

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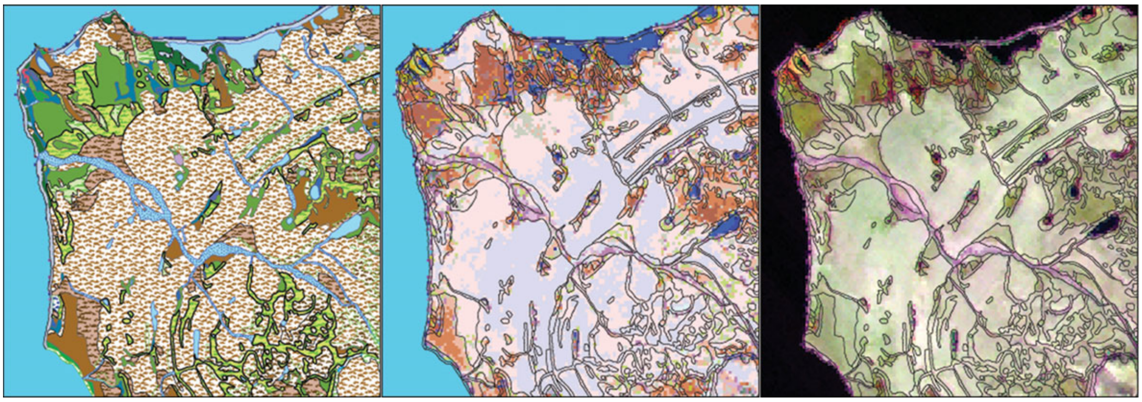

Fig. 10. Map subsections - Brøgger peninsula. The conventional map is displayed to the left, the satellite based map in the middle and a 3-band Landsat image (ch421) to the right.

Table 3. Accuracy test of aggregated classes from the produced map with correspondent data from a conventional vegetation map available from Gipsdalen valley (Elven and others1990).

Class units	Class overlap (%)
Water	74.71
Glaciers and snow	94.34
Dryas communities (open/established)	75.06
Moist marshes	39,32
Swamp/moss tundra	69.93
Gravel ridges/sedimentation flats	50.10
Established river fans	17.61
Exposed river plains (wet)	55.47
Overall accuracy	**55.36**
Average accuracy	59.56
Kappa Coefficient	**0.48**

species. Exposed sites of silt and gravel are displayed in red, while river fans are shown in purple colours.

The satellite based map gives almost an equal expression of the overall vegetation in the valley as in the conventional map. For *Dryas* communities the distinction between exposed and established community types appears in both map products. By following this distinction in accuracy assessment, the most exposed *Dryas* communities share high correspondence with other sparsely vegetated areas like non-vegetated gravel ridges, unstable river fans and gravel sedimentation flats. However, by aggregating all *Dryas* communities into one class the correspondence level is set to 75.06%.

The correspondence of comparable classes in the two map products is summarised in Table 3. As expected the classes of water and snow/glaciers show the highest values of coincidence within the material, with 74.71 and 94.34% of overlap respectively. The accuracy assessment further shows a correspondence of 69.93% for swamps and wet moss tundra, while moist marshes are recorded with an accuracy of 39.32%. These areas are found in small depressions in the terrain mainly found in the lower parts of the hill slope and to a large and varied area inside raised beach ridges.

In the satellite map the differentiation between wet and moist communities is drawn distinctly, combined with a distinction in fertility. The wet communities are mainly located in the valley floor in areas of stagnant

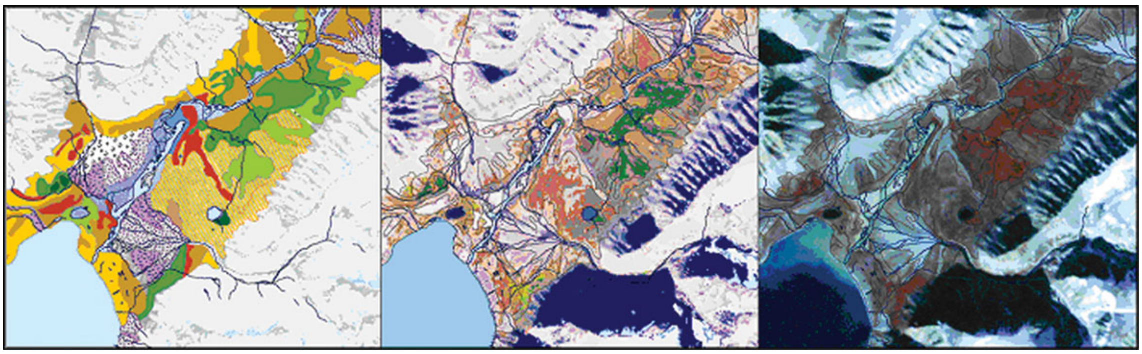

Fig. 11. Map subsections - Gipsdalen valley. The conventional map is displayed to the left, the satellite based map in the middle and a 3-band Landsat image (ch421) to the right.

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water, while moist communities are found in the mid parts of hill slopes. In the uppermost parts of the hill slopes open communities associated with areas of irrigating water are developed. For the remaining community types the correspondence values varies from 17.61 for established river fans to 55.47 for exposed river plains. Overall accuracy is set to 55.36 and average accuracy to 59.56. The Kappa coefficient was calculated as 0.48, which is characterised as moderate to substantial (Landis and Koch 1977).

Regarding hydrological conditions, two explanations can be given in order to describe the disagreement between the two map products. For wetland and marshes differences in hydrology are often connected with small depressions, drainage grooves and flats with standing water. These conditions often shift rapidly in the terrain. Satellite maps generally split such stands in different classes. In conventional maps this mosaic is often aggregated in complex classes. Further the moisture conditions in the subsoil vary with time giving rise to confusion problems when using satellite images. However, moist to wet communities are generally well detected in satellite images, mostly reflected due to spectral absorption in the MIR part of the spectrum. The vegetation density show the second prevailing gradient, reflected in the NIR part of the spectrum.

To summarise the comparison of the two map products, the main ecological differentiation within the area is drawn along the vegetation density and the hydrological gradients. Differences in hydrology are distinctly recorded in satellite images, especially in the MIR part of the spectrum. A more profound distinction is possible here by using SAR data as additional information. The variation in vegetation density is mostly reflected in the visible and in the NIR part of the spectrum as reflected in the 3-band image, Fig. 11 (right). Areas displaying light colours in this image are characterised by high reflectance in all channels. The general interpretation here is open areas often free of any vegetation cover, while darker image colors indicate more densely vegetated areas. Areas colored in red show fertile marshes and moss tundra communities.

Geographical occurrence of classes

To give an illustration of the occurrence and distribution of the recorded map units in a geographical context, class statistics for the overall area and for seven sub-regions are computed. The extents of sub-regions is defined by the authors but are also commonly accepted among researchers on Svalbard. The sub-sections are displayed in Fig. 12 and the class statistics are given in Table 4.

From the overall map and from the class statistics it is easily stated that the predominant landscape feature on Svalbard is constituted by the glaciers with an overall coverage of 36,860 km^2 representing 61.6% of the total area. The extent of glaciers varies highly from large ice

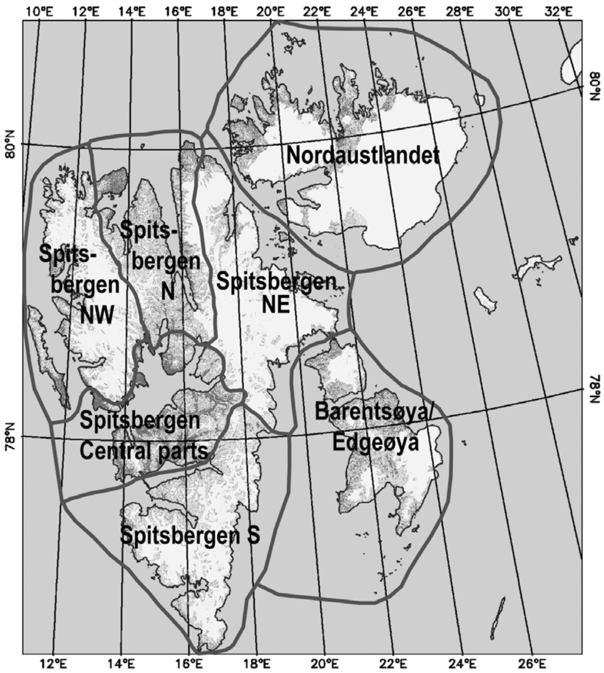

Fig. 12. Map of Svalbard with the 7 defined sub-regions.

caps in northeast to a huge number of small ones. The total number of glaciers recorded on Svalbard is more than 2,100 (Hagen and others 1993). All types of glaciers are represented. The most frequent types are the valley and cirque glaciers, especially located in Spitsbergen.

Regarding the non-glaciated land, the main landscape characteristics are associated with open, non- or sparsely vegetated areas. For the regions of Nordaustlandet, Spitsbergen-NE, Spitsbergen-NW and Spitsbergen-S the cover of non-glaciated land ranges from 18.0 to 31.6%. Most of these areas are seen as sedimentation flats, gravelly river fans, sterile talus slopes, recent moraines, bare rocks, boulder and gravel fields.

The more densely vegetated areas on Svalbard are mainly associated with the lowland. The three regions having the largest proportion of vegetated land are Spitsbergen-N, central Spitsbergen and the areas of Barentsøya and Edgeøya. The region of Spitsbergen-N is characterised by dry growing conditions due to low precipitation levels. Different types of *Dryas* tundra are developed along the Wijdefjorden, combined with specific 'steppe' communities on dry silt subsoil. The species *Potentilla pulchella*, *Poa abbreviata*, *Poa hartzii* and *Festuca baffinensis* are characteristic for these plains (Elvebakk and Nilsen 2002). In the northernmost parts of this region long lasting snow with large proportions of late snowbeds are more common.

For the regions of Barentsøya and Edgeøya glaciers constitute 44.2% of area. The vegetated areas here are surprisingly varied, especially along the western coast. Here dense vegetation of *Dryas* combined with *Papaver dahlianum* is developed in Discobukta, with well developed swamp and moss tundra communities near the

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Table 4. *Areal statistics for separated sub-regions on Svalbard.*

Regions	Map units	Nordaustlandet km²	Nordaustlandet %	Spitsbergen NE km²	Spitsbergen NE %	Spitsbergen N km²	Spitsbergen N %	Spitsbergen NW km²	Spitsbergen NW %
1	Sea, ocean	–	–	–	–	–	–	–	–
2	Inland water	142,7	1,0	35,9	0,4	62,5	0,9	48,4	0,6
3	Broad flooding rivers	6,1	0,0	32,5	0,3	38,9	0,6	51,2	0,6
4	Glaciers	11229,4	76,5	7657,4	82,0	2450,2	34,9	5477,4	68,4
5	Wet, non-vegetated areas	631,4	4,3	467,4	5,0	990,9	14,1	514,2	6,4
6	Dry, non-vegetated areas	426,4	2,9	381,3	4,1	521,5	7,4	503,3	6,3
7	Shadows, shade effects	135,0	0,9	233,6	2,5	1182,6	16,9	563,4	7,0
8	Pioneer-vegetation	150,2	1,0	48,0	0,5	215,3	3,1	150,6	1,9
9	Moderate snowbeds/snowflush com.	62,5	0,4	10,4	0,1	156,4	2,2	29,8	0,4
10	Swamp and wet moss tundra	0,0	0,0	1,3	0,0	23,9	0,3	6,8	0,1
11	Mires and wet marsh tundra	0,0	0,0	1,4	0,0	1,7	0,0	0,1	0,0
12	Moist tussock tundra	0,0	0,0	0,0	0,0	4,2	0,1	8,9	0,1
13	Exposed *Dryas* tundra	0,0	0,0	11,9	0,1	65,5	0,9	39,1	0,5
14	Established *Dryas* tundra	134,6	0,9	50,6	0,5	364,1	5,2	233,7	2,9
15	Arctic meadows	0,0	0,0	3,4	0,0	60,3	0,9	44,6	0,6
16	Exposed graminoid communities	67,6	0,5	11,8	0,1	29,4	0,4	14,3	0,2
17	Gravel barren communities	545,7	3,7	77,0	0,8	210,3	3,0	92,9	1,2
18	Gravel snowbed communities	1155,1	7,9	310,5	3,3	640,2	9,1	227,8	2,8
	Total	14686,7	100,0	9334,3	100,0	7018,1	100,0	8006,6	100,0

seashore flats. Comparable vegetation communities are described more to the north in Rosenbergdalen (Heinemeijer and van Dijk 2004). The eastern coast is highly glaciated with polar desert vegetation on dry sites and late snowbed communities on the coastal plains combined with sterile and loamy flats (Zonneveld and others 2004). Characterising species here are *Papaver dahlianum* and *Luzula arctica* on ridges, with *Ceratium regelii* and *Phippsia concinna* in depressions.

The region of central Spitsbergen is different from the remaining regions in several ways. The glaciers here only cover a minor proportion of the overall area. Different types of pioneer vegetation as well as late snowbed communities are associated with the recent moraines

Table 4. (continued). Areal statistics for separated sub-regions on Svalbard.

Regions	Map units	Edgeøya and Barentsøya km²	Edgeøya and Barentsøya %	Spitsbergen Central parts km²	Spitsbergen Central parts %	Spitsbergen S km²	Spitsbergen S %	Spitsbergen all regions km²	Spitsbergen all regions %
1	Sea, ocean	–	–	–	–	–	–	–	–
2	Inland water	20,7	0,3	30,6	0,6	38,8	0,4	379,5	0,6
3	Broad flooding rivers	78,4	1,2	80,2	1,5	179,6	2,0	466,9	0,8
4	Glaciers	2828,2	44,2	1001,5	18,5	6216,4	69,6	36860,5	61,6
5	Wet, non-vegetated areas	754,8	11,8	768,8	14,2	793,6	8,9	4921,0	8,2
6	Dry, non-vegetated areas	701,1	11,0	555,3	10,3	525,6	5,9	3614,5	6,0
7	Shadows, shade effects	386,0	6,0	815,2	15,1	698,2	7,8	4014,1	6,7
8	Pioneer-vegetation	197,9	3,1	310,7	5,7	98,0	1,1	1170,6	2,0
9	Moderate snowbeds/snowflush com.	0,0	0,0	92,5	1,7	10,8	0,1	362,5	0,6
10	Swamp and wet moss tundra	23,7	0,4	41,9	0,8	23,7	0,3	121,3	0,2
11	Mires and wet marsh tundra	49,4	0,8	82,1	1,5	16,6	0,2	151,4	0,3
12	Moist tussock tundra	0,0	0,0	182,5	3,4	10,6	0,1	206,3	0,3
13	Exposed *Dryas* tundra	351,6	5,5	140,8	2,6	42,7	0,5	651,7	1,1
14	Established *Dryas* tundra	322,4	5,0	410,0	7,6	82,2	0,9	1597,5	2,7
15	Arctic meadows	0,0	0,0	275,2	5,1	7,9	0,1	391,5	0,7
16	Exposed graminoid communities	6,5	0,1	143,7	2,7	10,8	0,1	284,0	0,5
17	Gravel barren communities	0,0	0,0	210,0	3,9	44,1	0,5	1180,1	2,0
18	Gravel snowbed communities	675,5	10,6	274,4	5,1	136,4	1,5	3420,0	5,7
	Total	6396,0	100,0	5415,4	100,0	8936,0	100,0	59793,1	100,0

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bounding the glaciers. In the broad lowland valleys the valley floors comprise large areas of hygrophilous marshes, swamp and moss tundra vegetation. Different types of *Dryas* tundra vegetation are well developed on ridges and in hill-slopes. Further luxuriant arctic meadows are developed, most often found in south-facing slopes. Large areas of these community types are found on Dickson Land, and in the valleys of the inner fjord zone.

One of the main topographic features of the region is the smaller and bigger valleys dissecting the Nordenskjöld Peninsula from different directions. The valleys tend to be evenly spaced by river outlets from tributary valleys constitute different types of river fans in the main valley. The rate of flow, mainly as melt water from the glaciers, highly affects the shape and extent of the established fans. The vegetation on river fans can be differentiated into unstable and established formations, in which the unstable river fans are often an initial stage of an overall stabilisation process. The single most important plant for stabilisation of river fans in the area is *Saxifraga oppositifolia*, weaving a net of long rooting branches through the gravel and silt. Some stabilisation is also attained by species like *Salix polaris*, *Bistorta vivipara*, *Stellaria loggipes* coll. and different grass species. Vegetated river fans are among the most species rich habitats in the area, especially in the inner fjord zone. To some extent dense *Dryas* tundra constitute the vegetation cover at the most stable parts of the river fans.

Discussion

Large scale mapping of Arctic vegetation

When working out vegetation maps utilising satellite images, the main challenge is to bridge the information extracted from satellite images with the variation in vegetation at the mapping site. Several factors may account for this variation. For arctic areas climate parameters, mainly associated to low temperatures and water deficient, are the main determinant for limiting the northern ranges of vegetation and plant growth (Tuhkanen 1984; Moen 1999; Karlsen and others 2005). Due to harsh climate conditions Arctic areas are characterised by open landscapes. Exposed ridges, sedimentation flats, gravelly river fans, steep talus slopes, recent moraines as well as bare rocks, boulder and gravel fields are landscape elements characterising large areas.

In a geographical context the vegetated areas are particularly located in the central and western parts of the island of Spitsbergen, while the northern and eastern areas are highly glaciated. The main explanation for this distinction in vegetation composition is the sea currents bounding the archipelago. The warm west Spitsbergen sea current, flows along the western continental slope towards the north. The area west of the shelf is essentially ice-free most of the year (Aagaard and others 1987; Gascard and others 1995). On the eastern side the cold eastern Spitsbergen current, carries Arctic water between Svalbard and Zemlya Frantsa Iosifa and further southward along the coasts of the eastern islands (Loeng 1991; Pfirman and others 1994). The sea currents not only affect the sea temperatures, but also the temperature on shore (Bhatt and others 2010; Jia and others 2009). The cooling effect of the arctic seas is common throughout large parts of the Arctic and northern Eurasia (Razzhivin 1999). Low clouds or fog concentrate above sea ice or cold open water. The cooling and shading effects can be experienced deep inland if there are no natural barriers such as mountains to protect the inland areas. The cooling effect in the northern and eastern areas and warming effect in the west are important to explain the overall bioclimatic conditions on the archipelago.

Temperature effects on plant growth operate in different manners (Billings 1987). In general the photosynthetic activity, respiration and transpiration decreases with decreasing temperature. Further flowering of several plant species are triggered by specific temperature conditions. Buds of plants require exposure to certain number of days below a critical temperature before resuming growth in the spring. Finally temperature affects the length of the growing season for several plant species.

Elvebakk (1999) has summarised the previous attempts to define and subdivide Arctic areas into bioclimatic zones and sections. At overall scales the proposed divisions mainly rely on meteorological data, growth forms, distribution of permafrost and distribution of plant species sensitive to specific climate conditions. The defined criteria are further compiled into a map format with a subdivision of Arctic into five bioclimatic zones (Elvebakk and others 1999). In this context the archipelago of Svalbard is located in the three northernmost zones. From the criteria, constituted growth forms in lignified species and vegetation physiognomy is considered the most precise and user friendly primary criteria in this map abstraction. Recent studies have further incorporated varied types of information extracted from satellite images as important elements of division, like NDVI, coverage of snow and glaciers, as well as time series reflecting phenology of growth and thereby the length of the growing season (Jia and others 2002, 2003; Walker and others 2003; Karlsen and others 2006). Further a more profound use of community types extracted from vegetation maps are recommended in this type of delimitation.

It is out of the scope of this paper to put forward a modified proposal of zones and sections on Svalbard. However, by consulting the map product for the entire archipelago (Fig. 3) and the regional areal statistics (Table 4), new knowledge of the established zones may be summarised. The northernmost Arctic Polar Desert Zone (APDZ) appears to be characterised by glaciers and non- to sparsely vegetated land bounding the glacial regions. The main vegetation differentiation is along the dry-moist gradient with cryptogam herb barrens on dry sites and moist cryptogam tundra in areas with long lasting snow cover. On Svalbard large parts of the northeastern and eastern areas of Spitsbergen, the island of Nordaustlandet and the eastern parts of Barentsøya and

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Edgeøya definitely belong to this zone. Correspondent growing conditions are also recorded for large parts of NW-Spitsbergen. Based on this an inclusion of this region into the APDZ are to be considered.

The Northern Arctic Tundra Zone (NATZ) shows a much higher variation in community types, but still the glaciers and non- to sparsely vegetated areas constitute the main landscape feature. Community types of *Dryas octopetala* are frequent on ridges, terraces and in lower parts of hill slopes. Pioneer vegetation associated with instable river fans is common due to melting effects from surrounding glaciers. Moderate snowbed and snowflush areas are most common along the coast, as well as *Deschampsia alpina* tundra mires. The coastal plains are characterised by *Saxifraga oppositifolia* combined with the lichen *Cetraria delisei*. Three geographical sub-regions can be differentiated: a) coastal regions along the western coast b) continental areas, especially along Wijdefjorden, and c) the western parts of the Barentsøya and Edgeøya islands.

The Middle Arctic Tundra Zone (MATZ) is mainly located in the central fjord area, but also includes the coastal regions of Nordenskiöld Land. The general picture of this sub-zone is a fairly dense vegetation cover in the lowland, but also vegetated areas in the mountain areas. The community types in the lowland are varied constituting productive marsh vegetation in the valley floors, swamp and moss tundra vegetation on wet habitats, densely vegetated heather tundra in the hill slopes often characterised by *Cassiope tetragona* and open *Dryas-Carex rupestris* communities on ridges. The river fans are partly established, partly exposed. A characteristic feature of the area is a high number of species, many of them locally warmth demanding.

Mapping at local and regional scales

At local scales the main challenge is to produce reliable maps in coincidence with the vegetation scheme valid for the study area. This scheme has been established mainly on phytsociological approaches. In conventional vegetation mapping vegetation habitats are defined based on occurrence of species and vegetation cover. The vegetation stands are recorded on aerial photographs and further converted into map formats. Utilising this method, even low frequency species may be highly indicative for the definition of stands. The classification underlying conventional methods are further subjective, relying highly on the researcher and his interpretation of the vegetation formation. Many entities occur in stands too small to be outlined in the maps. Others are found regularly together in a mosaic pattern. Such complexes are mapped as a combination of two or more entities. In other cases mapping entities are collective, including several closely related vegetation communities.

Different from conventional mapping the classification of satellite images relies highly on differences in reflectance properties of the vegetation communities and their sites of growing. Utilising Landsat data in the map production process the reflectance properties can be drawn along three main gradients. Firstly, the visible channels differentiate the cover along a density gradient. In the visible part of the spectrum the difference between glaciers/snow and non-glaciated land is easily detected. Vegetated areas here show low reflectance values, while rocks, gravel barrens and non-vegetated flats all show intermediate to high reflectance values.

A second gradient, the fertility of the vegetation cover, is mainly expressed in the NIR part of the spectrum. Here the reflectance values are increased as chlorophyll content in the vegetation increases. On Svalbard the highest NIR values are recorded for vegetated areas associated to hygrophilous marshes, arctic meadows and dry grass communities. The lowest NIR values are recorded for open water, while sparsely vegetated communities like gravel barrens, gravel snowbeds and pioneer vegetation show somewhat elevated values, but still low. The heather tundra communities are here placed in an intermediate position.

The third important gradient associated with Arctic vegetation is the degree of wetness on the growing site and the moisture content in the vegetation layer. Information on stand wetness is expressed in the MIR part of the spectrum. This means that cover types and vegetation being influenced by high water content show naturally low MIR responses. On Svalbard the swamps, wet moss tundra and wet snowbed communities are all recorded with low MIR values. The lowest MIR values recorded among the classes separated are seen for open water and for the glaciers. The highest MIR values are recorded for dry grass communities, and community types on gravel, barrens and on dry, loamy subsoil.

Reliability of the produced map

By comparing conventional vegetation maps with the satellite based map developed in this project, both differences and equals are detected. The differences between the maps are mainly related to the most detailed level of differentiation where the growth conditions are more or less equal, but differences in floristic composition are used to distinguish one community type from another. Pure stands of *Dryas octopetala* on dry sites are in most cases not differentiated from correspondent stands dominated by *Cassiope tetragona*. Differences between grass and sedges in marshes, differences in moss species in snowbeds and differences in lichens and sedge species in open tundra heather communities are other examples of differences only being captured through conventional mapping and extensive field surveys.

Some of the differences detected are further associated with land cover changes in some areas. This is especially the case for the test site of Brøgger Peninsula. After more than 100 years without any reindeer on the peninsula, 15 animals were placed here in 1978. In the years after the stock of herd increased rapidly to 31 animals in 1980, 200 animals in 1989, until the top was reached in 1994 with more than 360 animals. This expansion in the animal numbers had dramatic effects on the vegetation cover and composition within the area. A general loss in plant cover was recorded for all groups of species. Especially the depletion of lichens was dramatic. These changes in vegetation cover are likely seen when comparing the conventional vegetation maps from Brøgger Peninsula with the satellite based map based on data from the year 2000.

Despite the discrepancies between the two map products, the equality between the maps describes the possibilities of using satellite images in mapping Arctic areas. The major features in the landscape are reflected in both map products. Both products draw a distinct separation between vegetated and non-vegetated areas. In both map products the distinction between dry, moist and wet vegetation communities are highly reflected. Finally in both map products heather tundra communities are arranged distinctly along a gradient from open to established community types.

Conclusions

The approach described in this paper has yielded a new vegetation map of the Svalbard archipelago. The map is produced through a standardised map production scheme combining several Landsat images into a seamless, generalised and consistent vegetation map product. The product represents a new and different approach of viewing vegetation cover and content on Svalbard.

The potential use of the data set is many, especially related to regional analysis, habitat studies of northern birds and animals, bioclimatic studies and studies associated to climate change. A preliminary version of the produced map has already been used in management analysis of geese population on Svalbard (Jensen and others 2008; Speed and others 2009).

Regarding climate change studies the potential use of the produced map is highly relevant for the predicted 'greening of the Arctic' (Walker and others 2003). A rise in temperature in northern areas will affect the plant growth in terms of increased photosynthetic activity, increased respiration and transpiration, which in turn increases the net primary production. It is particularly important for the management of arid and northern ecosystems to understand the factors controlling phytomass production. Several studies state that the mean above ground net primary production (ANPP) of arid systems is strongly correlated with mean annual precipitation (Wiegand and others 2004), while temperature is the main controlling factor for northern and Arctic systems (Keeling and others 1996).

The invasion of southern species into northern habitats is another area in which changes are expected. Recent studies in northern Scandinavia have shown that shrub encroachment and tree invasion into the open tundra landscape have been much more rapid than previously expected (Kullman 2002; Tape and others 2006). These vegetation changes increase the amount of solar radiation absorbed and converted into heat (Chapin and others 2005). There is also a positive feedback loop between canopy cover and snow melt, which can have dramatic impact on ground albedo in the spring period. These feed back effects are ominous for northern biota and cultures dependent on a cold climate for their way of living.

This project can be viewed as a first step towards a generation of a base line intermediate scale vegetation map for Svalbard. The product shows high correlation with conventional maps for western parts of the archipelago, but suffers from lack of verification data for large parts of the northern, eastern and southern regions. Despite the progress in vegetation mapping during the past decades, the methodologies for mapping different vegetation types over broad geographic areas are still undeveloped. Many mapping strategies rely on either subjective observations covering small areas, or division of broad geographical areas into large-scale zones and sections.

In the production scheme described in this study a combination of satellite data and ancillary information is used to create the final map product. The difficulty involved in mapping cover types based on satellite data, depends highly on the level of detail represented in the data type and in the accuracy of the ancillary data. In the years to come new and more 'fine-grained' data for the areas of Svalbard will be available, combined with improved topographic maps. Further specific map layers displaying the variation along important ecological gradients on the archipelago are to be developed. This will initiate the second step in the map production process for Svalbard.

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Linear spectral mixture modelling of arctic vegetation using ground spectroradiometry

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ABSTRACT. An experimental linear mixture modelling using ground spectroradiometric measurements in the Kola Peninsula, Russia has been carried out to create a basis for mapping vegetation and non-vegetation components in the tundra-taiga ecotone using satellite imagery. We concentrated on the ground level experiment with the goal to use it further for the classification of multispectral satellite imagery through spectral unmixing. This experiment was performed on the most detailed level of remote sensing research which is free from atmospheric effects and easy to understand. We have measured typical ecotone components, including *Cetraria nivalis*, *Betula tortuosa*, *Empetrum nigrum, Betula nana, Picea abies* and rocks (nepheline syenite). The result of the experiment shows that the spectral mixture is indeed formed linearly but different components have different influence. Typical spectral thresholds for each component were found which are significant for vegetation mapping. Spectral unmixing of ground level data was performed and accuracy was estimated. The results add new information on typical spectral thresholds which can potentially be applied for multispectral satellite imagery when upscaling from high resolution to coarser resolution.

Introduction

Mapping of the current state of the vegetation of the forest-tundra interface, or ecotone, and its dynamics is very important because it is a sensitive long term indicator of global climate changes. The forest-tundra ecotone stretches for more than 13,400 km around the northern hemisphere, separating the boreal forest to the south from treeless tundra to the north (Callaghan and others 2002). These large and remote areas have great potential to be surveyed by remote sensing methods (Rees and others 2002). The most common way of remotely sensed data processing is image classifications which form the basis of subsequent land cover maps.