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MAPPING TO ASSESS REVEGETATION ACTIVITIES AND TO ESTIMATE CARBON SEQUESTRATION: A CASE STUDY OF KRYSUVIK, ICELAND

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ABSTRACT

The study was carried out in Krýsuvík in south-western Iceland where land degraded by heavy sheep grazing is being restored through revegetation by the Soil Conservation Service of Iceland (SCSI) beginning in the 1980s. The objectives of the study were to: (1) compile existing data to make a map of the revegetated areas, (2) establish a geographically identifiable time series of revegetation activities and (3) recalculate the amount of carbon sequestration based on the estimated revised area. An area of 14 km² was selected for the study to re-estimate revegetated areas and carbon sequestration by using remote sensing and GIS techniques. Two aerial photographs of 1989, 1992 and a SPOT 5 image of 2009 were used for digitizing restored areas. A map of the revegetated area was produced by placing the digitized area on top of the SPOT 5 image. The accuracy of the map was assessed using an error matrix, following random sampling techniques. With an overall accuracy of 55%, the map is seen to have a low overall accuracy compared to the recommended overall of 85%. Revegetated areas sizes, and the amount of carbon sequestered were recalculated with and without overlapping for the all SCSI activity area, study areas, and the digitized areas. The results of the study showed that the all SCSI activity areas are much bigger than the activity areas obtained from digitization of images. This may be due to the use of overlapping areas by the SCSI when recording revegetation areas. Overlapping should be excluded when recording revegetation activities to avoid double counting of activity areas which can give rise to an overestimation of carbon sequestration.

Keywords: overlapping, revegetation, carbon sequestration, activity area, remote sensing

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1. INTRODUCTION

1.1 Land degradation

Human beings rely on land for goods and services necessary for their livelihood. By overexploiting land and associated natural resources through overgrazing, deforestation, fragmentation and urbanization to satisfy his continuous needs, man contributes to land degradation. Land degradation which is collectively caused by anthropogenic and natural factors is a huge problem facing different parts of the world in this 21st century. It affects 30 to 50% of Earth's land surface, and includes as immediate causes both biophysical causes and unsustainable land management practices (Pimentel 1993; Nkonya et al. 2011).

In Niger, land degradation occurs through water and wind erosion and causes a decrease in crop production, siltation of water bodies, damage to socio-economic infrastructure (buildings, roads, schools and health centres) and human health (World Bank 2009). Degradation of soil and vegetation cover is extensive in Iceland, due to its past centuries of severe soil erosion processes resulted from overgrazing, deforestation and harsh ecological conditions. The problem started 1100 years ago with the country's settlement, combined with various volcanic and glacial activities (Arnalds 1987; Arnalds et al. 2001).

1.2 Land restoration

Seriously degraded lands lose their capacity of self-repairing and the ability of preventing additional degradation (Whisenant 1999). Disturbances in the Icelandic environment in many places crossed the threshold so that they cannot recover if left alone (Gisladottir 1998). Therefore, restoration efforts were required to reverse the trend of degradation in these areas. Restoration has gained much interest in recent years, because it helps to re-establish the functionality and the productivity of degraded land (Ibrahim 2010; Laestadius et al. 2012a). According to Laestadius et al. (2012a), it is through efforts of restoration that countries such as China, Niger and the United Republic of Tanzania are reducing the rate of desertification and restoring degraded environments, thereby improving the socio-economic conditions of their populations.

In Iceland, systematic protection and restoration of vegetation cover and soil started in 1907 with the establishment of the Soil Conservation Service of Iceland (SCSI), whose primary objective was to stop the problem of drifting sand (Crofts 2011). Protection and reclamation activities such as the fencing off of restoration areas, construction of stone walls, afforestation and revegetation have been carried out by SCSI in different parts of the country to halt the destructive forces of erosion and to revegetate degraded lands.

1.3 Revegetation

The present research work was only focused on revegetation activities as a means of reclaiming degraded land. Revegetation is defined as treatments aimed at restoring ecological processes on degraded lands (Arnalds et al. 2000). Revegetation is one of the activities recognised by the Kyoto protocol as a method to sequester carbon. As such, it is clearly defined in the Environment Agency of Iceland's National Inventory Report of 2013 as:

> A direct human-induced activity to increase carbon stocks on eroding or eroded/desertified sites through the establishment of vegetation or the reinforcement of existing vegetation that covers a minimum area of 0.5 hectares and does not meet the

definitions of afforestation or reforestation (Environment Agency of Iceland 2013, p. 141).

In Iceland, revegetation of degraded land consists of seeding with herbaceous and/or grass species and fertilizing with mineral fertilizer and fencing off areas. Then, fertilize again the treated areas in the next one or two years to enhance establishment of the seeded grass species. Revegetation not only contributes to the restoration of degraded lands but also to the sequestration of carbon dioxide by soil and vegetation. Therefore, it is considered by the international community as one of the ways by which the Kyoto protocol can be implemented. Thus, among important measures taken by the Icelandic government with regard to the implementation of the Kyoto protocol to the Framework Convention on Climate Change (FCCC) are efforts to sequester carbon by restoring severely degraded lands (Arnalds et al. 2000). Therefore, from 1990 to 2011, 87090 ha were revegetated (Environment Agency of Iceland 2013).

1.4 Carbon sequestration

Country specific factors should be considered when estimating carbon sequestration under revegetation management (IPCC 2006). This means that estimation of carbon is principally based on scientific research at the national level. Actually, different approaches have been developed by scientists for the estimation of carbon sequestration in conformity with the Kyoto protocol (Namayanga 2002). Arnalds et al. (2000) estimated the soil carbon sequestration rate under reclamation at 0.6 t C/ha/yr for > 50 years, while Aradóttir et al. (2000) estimated the aboveground biomass sequestration per year to range from 0.01 to 0.5 t C/ha. A recent study has estimated the annual soil carbon accumulation rate at 0.04-0.063 kg C/m2 for the first seven years after restoration and > 0.05 kg C/m2/yr that can be maintained over 100 years (Arnalds et al. 2013). The carbon sequestration rate is affected by factors such as time of treatment, ecological conditions, soils and land use type (Jobbágy & Jackson 2000; Chapin III et al. 2009; Arnalds et al. 2013).

Carbon sequestration is estimated based on extensive measurements (Environment Agency of Iceland 2013). An emission factor of 0.57 t C/ha/yr is actually used in Iceland for carbon sequestration under revegetation. Iceland ratified the Kyoto Protocol on May 23rd, 2002, and therefore for its first commitment period (2008-2012) should not increase its greenhouse gas emissions more than 10% of the level of emissions in 1990 (Environment Agency of Iceland 2013). Iceland reports carbon removal (sequestration) under articles 3.3 and 3.4 (revegetation) of Land Use Land Use Change and Forestry (LULUCF) for the entire commitment period (Environment Agency of Iceland 2013). Carbon removal due to revegetation for the four years is estimated at 653,194 Gg CO_2, while the total removal is estimated at 1,169,833 Gg for the same period (Environment Agency of Iceland 2013).

1.5 Statement of the research problem

Revegetation is one of the ways chosen by the Icelandic government to implement its commitment to the Kyoto protocol. Important revegetation activities are carried out throughout the country by specialized institutions such as the SCSI to fulfil this commitment. However, efficient reporting of carbon sequestration through revegetation is only possible with the availability of reliable data on revegetated areas per year, the period passed under revegetation, removal of overlapping areas (treated areas of a year accounted for more than one year) and old vegetation areas (i.e. vegetation remaining undisturbed by erosion).

This study aimed at checking in Krysuvik in south-western Iceland the recorded and mapped revegetation activity by re-estimating the activity areas and recalculating carbon sequestration on the basis of the new estimated area.

1.6 Objectives of the study

The general objective of this study was to assess the revegetation activity areas in Krysuvik by applying different geographical methods. The specific objectives were:

1. To compile existing data to make a map of the revegetated areas in Krysuvik;
2. To establish a geographically identifiable time series of revegetation activities;
3. To recalculate the amount of carbon sequestration based on the estimate for the revised area.

1.7 Importance of the study

The importance of the present study is:

- Development of a revegetation map for the study area that can serve as a model in the future to elaborate the map of the total revegetation area of Krysuvik;
- Recalculation of the quantity of carbon sequestered by the study area which also can be used to estimate the total carbon sequestered through revegetation in Krysuvik and the percentage it represents of the annual carbon reported by Iceland.

2. LITERATURE REVIEW

Mapping is used in restoration activities such as revegetation, reforestation and afforestation to identify, assess or monitor natural resources (land, soil, vegetation, and wildlife). It is one of the principal components of conservation planning and management systems (Lawson 2006). In restoration activities, maps provide details on the geographical position of land and its potential opportunities for restoration but not on the type of restoration treatment (Laestadius et al. 2012a). Mapping is used to identify abundant potential areas for restoration opportunities in the world for many countries that have suffered forest loss and degradation (Laestadius et al. 2012a; Laestadius et al. 2012b). Mapping is also used in restoration for prioritization. Hence, Kramer and Carpenedo (2009) developed a set of maps to identify prioritized wetlands restoration sites combined with human impact that threaten aquatic resources at watershed level in the state of Georgia in the USA, using among other methods a land use trends database and soils map. These maps can help natural resources managers all over that state to base their restoration efforts in areas with high cumulative impacts on the health of the wetland ecosystem and the surrounding communities.

Apan et al. (2004) prepared a map for prioritization of revegetation in a dryland area water catchment where a salinity problem resulted from overcutting perennial vegetation that could affect the re-establishment of new vegetation. To achieve this work, they mapped the recharge and discharge zones of the catchment and gave priority for revegetation to the recharge zone with a low concentration of salt and abundant water. The discharge zone had a high concentration of salt and was therefore found to be unfavourable to plant growth and good crop yields. In addition, maps are elaborated for estimation and analysis of the ecological conditions and functions of degraded grazing lands (Gisladottir 1998) or to provide information and evaluate the natural and cultural environment (Gisladottir 1993). They can also be prepared to determine the extent of land degradation (Thompson et al. 2009) and restoration efforts of vast areas for a specified period of time (Velázquez et al. 2003; Aide et al. 2012) or the abandonment of croplands together with restoration activities such as natural revegetation and afforestation (Ivanov et al. 2007).

3. METHODS OF THE STUDY

3.1 Study area

The study area covers approximately 14 km² and is located in Krysuvik on the Reykjanes Peninsula in south-western Iceland. It originally had an important vegetation cover suitable for communal grazing lands which has been degraded by intensive sheep grazing over the last 200 years (Gisladottir 1998). Krysuvik has also been subjected to volcanic eruptions during the ice free periods (Kamah 1996) and thus contains many old lava flows. With cool and windy weather, the area has a mean annual temperature of 5ºC and receives a mean annual precipitation of 1400-2200 mm (Gisladottir 1993). Revegetation started in Krysuvik in the 1980s (A. Arnalds, 12 September 2013, Soil Conservation Service of Iceland, personal communication). Interest in revegetation increased with the agricultural policy of 1979 which limited sheep farming and the realignment of farm goals to land reclamation actions (Gisladottir & Preston-Whyte 1998). Figure 1 presents maps showing the study area and all SCSI activity areas in Krysuvik.

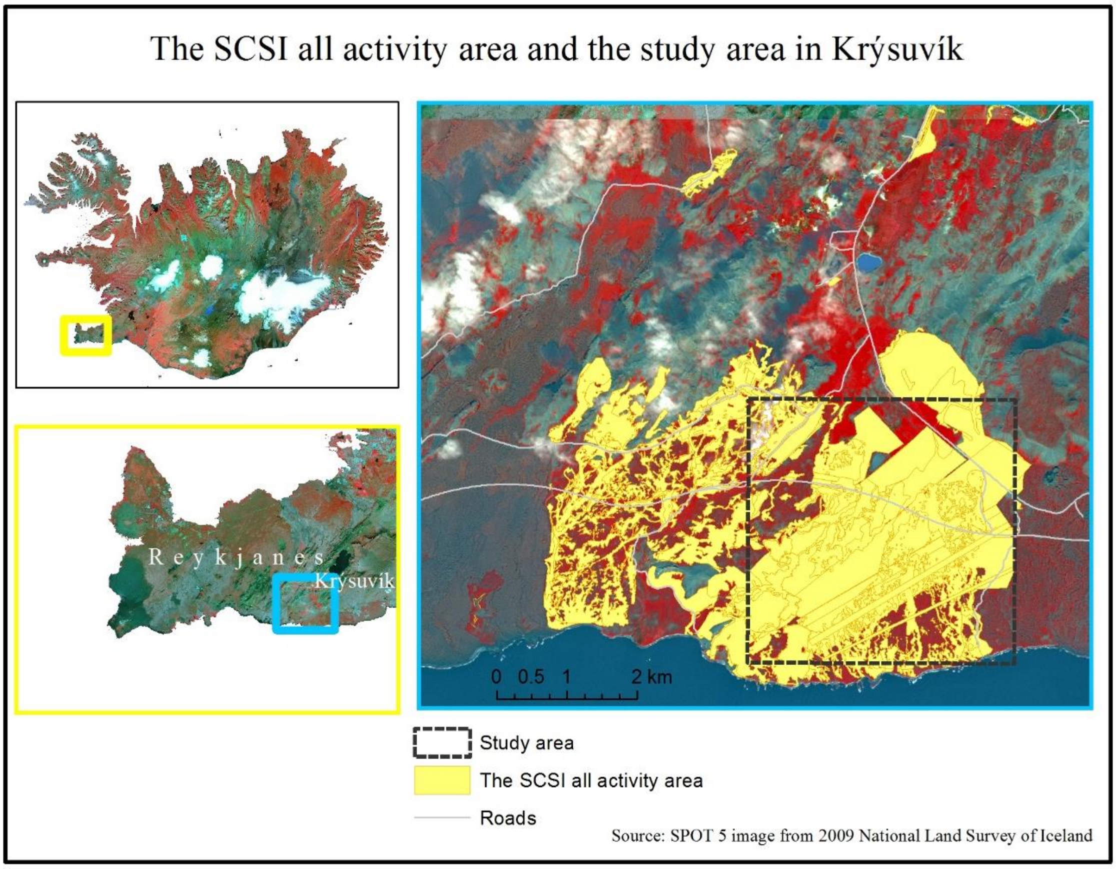

Fig. 1. *Maps showing the entire activity site (in yellow) of SCSI in Krysuvik and the study area (marked with black dot lines) on Reykjanes Peninsula. On the SPOT 5 image vegetated areas are in red and non-vegetated areas in green.*

3.2 Datasets

The study consisted of using recorded areas of revegetation activities and an available activity map for each year, exclude overlapping areas, and to digitize identifiable revegetation activities on aerial photographs and satellite images. Estimated areas and carbon sequestration were then compared. Available good quality images covering the entire SCSI activity area in Krysuvik were examined and three of them were chosen for the study. The following data were used:

- L 1125, a black and white aerial photograph of 31st July, 1989;
- M 1180, a colour infra-red aerial photograph of 22nd July, 1992;
- SPOT 5 satellite image taken in 30 August, 2009;
- Roads layer of Krysuvik;
- Information on activities of the SCSI from 1990 to 2009 was acquired from written records and a map of these realized activities of the area drawn from the SCSI database.

M 1180 has a spatial resolution of 0.5 m x 0.5 m, while L 1125 has a resolution of 0.8 m x 0.8 m and SPOT 5 a resolution of 2.5 m x 2.5 m. All the images were obtained from the National Land Survey of Iceland.

3.3 Geometric correction of images

Geometric correction is a process by which distortions on the images are eliminated (Xie et al. 2008). It is obtained by establishing a relationship between the image coordinate system and the geographic coordinate system using the calibration data of the sensor, the measured data of position and altitude, and the ground control points. The SPOT 5 image was obtained geometrically corrected from the suppliers, while the aerial photographs L 1125 and M 1180 were not. Therefore, L 1125 and M 1180 needed to be corrected. This correction was done with Arc Desktop 10.1 software using the Spot 5 image and a shape file of the roads of Krysuvik as reference.

3.4 Digitization

According to Bolstad (2005), manual digitizing is the process of interpreting and converting a paper map or image data to vector digital data. This process was used to draw the revegetated areas of the L 1125, M 1180 aerial photographs and the SPOT 5 satellite image using the SCSI realized activities in Krysuvik for individual years from 1990 to 2009 as reference. Visible stripped areas representing signs of activity by SCSI aeroplanes or tractors on L 1125 and M 1180 were digitized using Arc Desktop. On the SPOT image, areas in a greenish-red colour (not too red) corresponding to new vegetation were digitized.

In this document, the meanings of different terms used for areas are given as follow:

- Study area excluding overlapping: Areas inside the study area obtained from SCSI activity map;
- Study area including overlapping: Areas inside the study area obtained from SCSI activity map;
- Digitized area excluding overlapping: Revegetated area digitized from the three images;
- Digitized area including overlapping: Revegetated area digitized from the three images;

- All SCSI activity area excluding overlapping: The revegetation area in Krysuvik that excluded overlapping areas, obtained from the activity map layer of SCSI;
- All SCSI activity area including overlapping: The revegetation area in Krysuvik that included overlapping areas, obtained from the activity map layer of SCSI.

3.5 Field survey

A field survey was realized to get familiar with the study area, its vegetation and terrain forms, and predefined plots, and to verify the existence of revegetation activity on the ground. Data collected from this survey were used to evaluate the accuracy of the reclaimed vegetation area, digitized from the aerial photographs and used for the study. It was decided for this purpose to have no fewer than 30 plots using Arc GIS. At the end 33 plots of approximately 10 m x 10 m were randomly selected. These plots were examined, classified and recorded (Fig. 2) under three categories, namely new vegetation on reclaimed area (Fig. 2), old vegetation on undisturbed area (Fig. 3), and no vegetation (Fig. 3). In addition, five photographs were taken of each plot, one in each cardinal direction along with one vertically downward, to support the condition and state of each plot.

Fig. 2. *Recording GPS points for plots (left) (Photo: A. B. Thorsteinsdottir, 29 July 2013). New vegetation (right). (Photo: M. H. Gabou, 29 July 2013).*

Fig. 3. *Old vegetation (left). No vegetation (right) (Photos: M. H. Gabou, 29 July 2013).*

For easy and quick access in the field, the plots were selected and located within a distance of 200 m or less from the roads in the study area (Thorsteinsdottir 2011). A total buffer zone of 4.12 km² was therefore formed. Plots are distributed throughout the buffer zone, using a 500 m x 500 m grid in ArcGIS. Each grid cell contains 2 plots. Thus, all parts of the gridded area were randomly assigned plots. The road data used to create the buffer are vector data from the National Land Survey of Iceland measured by GPS and used as an overlay in ArcGIS. The accuracy of the position as measured by Magellan Meridian GPS units (position corrected by WAAS/EGNOS) is +/- 3 m (Map-GPS-Info.com 2011; MiTAC International Corporation 2011).

3.6 Accuracy assessment

Accuracy assessment is required when aerial photographs and satellite images are used to develop a revegetation map (Congalton 2005). An error matrix, the most used accuracy assessment (Foody 2002; Milne et al. 2010), was used to assess the revegetation map that resulted from this study. In the matrix, the rows represent digitized areas from each image and the columns the field data (reference data). Agreement between the assigned digitized areas on the image and the field data is indicated by the main diagonal of the matrix (Congalton 2005).

Different accuracies were obtained with the error matrix. The producer accuracy is the probability that a reference land cover is well classified and the user accuracy the probability that a classified land cover on the map or image is exactly the same land cover on the ground (Congalton 1991). The overall accuracy is obtained by dividing the number of the main diagonal of the matrix by the total of the column (Story & Congalton 1986). With an error matrix, a minimum overall accuracy of 85% and not less than 70% for other accuracies is required for a given map to be designated accurate (Thomlinson et al. 1999; Foody 2002). However, this requirement is not universally accepted by other scientists (Foody 2002).

3.7 Recalculation of carbon sequestration

The amount of carbon sequestered by the revegetation was calculated using the emission factor (EF) and the area treated per year from 1990 to 2009. The area treated for each year was obtained by GPS measurements and description from the field workers. This new area was added to the total of areas treated in previous years, after removing overlap. The following formula was used for the calculation of the carbon sequestration: CS= EF x A, where CS stands for carbon sequestration, EF the emission factor and A for area. The new carbon sequestration emission factors applied for below and aboveground, for "other land converted to grassland" were respectively 0.06 and 0.51 t C/ha/yr. Therefore, for the estimation of carbon sequestration in this study, an emission factor of 0.57 t C/ha/yr was used.

4. RESULTS

The results of this study were as follows: the map of revegetation of the study area, estimated revegetated areas of the study area, and of SCSI all activity areas and their amounts of carbon sequestration. It is important to note that the activity area sizes were estimated based on a time series of revegetation activities from 1990 to 2009 that had been established.

4.1 Revegetation map of the study area

The revegetation map of the study area was developed on top of an infrared SPOT 5 image of 2009. This map represents all the digitized areas of the images of 1989, 1992 and 2009 (Fig. 4).

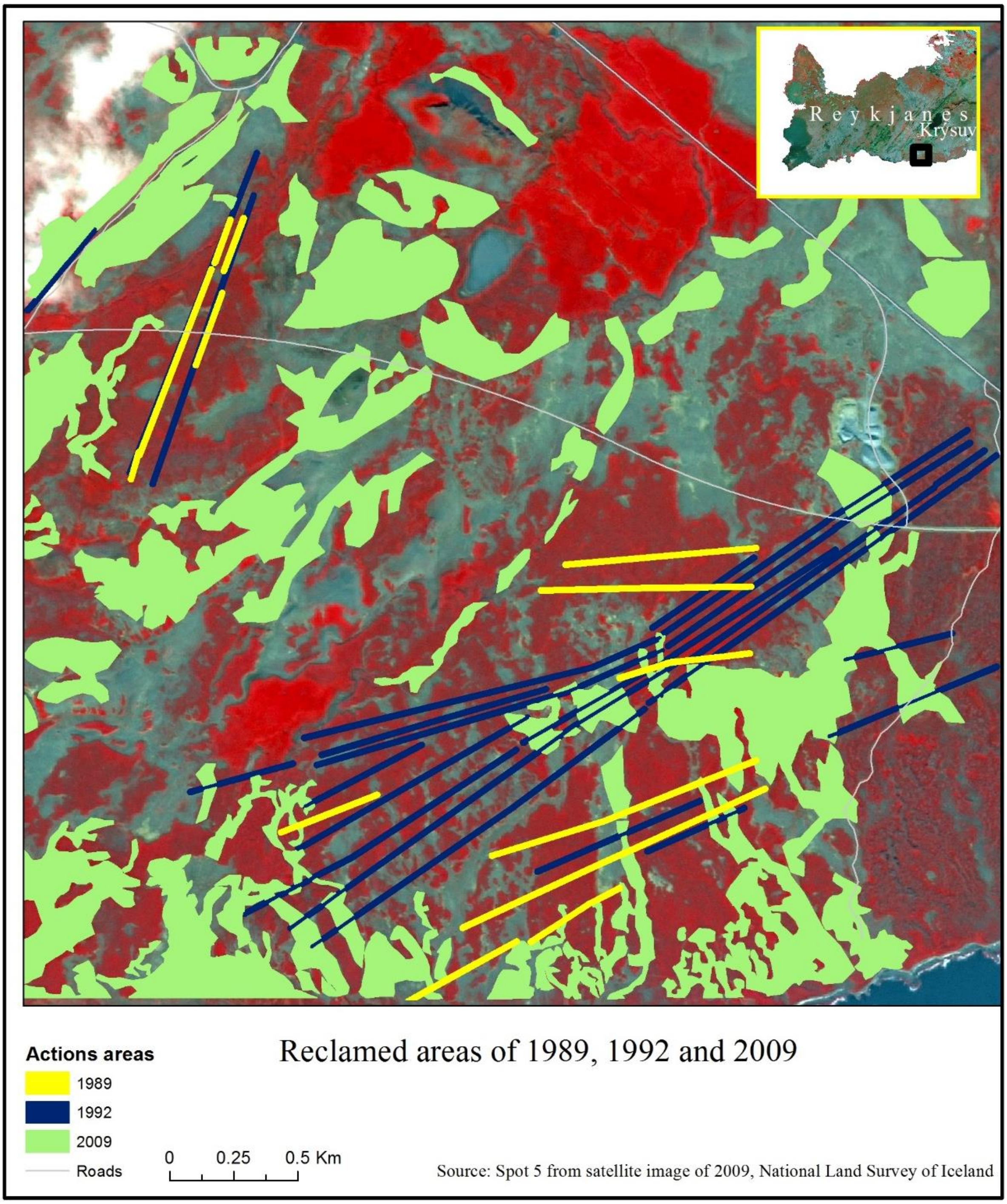

Fig. 4. *Revegetation map obtained by combining digitized action areas in images from 1989, 1992 and 2009 onto SPOT 5 image. Digitized action areas are shown in different colours in the photograph. Vegetated areas are in red and non-vegetated areas in green.*

4.2 Accuracy assessment

Information collected from the field survey was used to carry out an accuracy assessment for the developed revegetation map by means of an error matrix, as shown in Table 1. It is important to note that 4 of the 33 randomly selected plots were not reachable for the sampling (no access roads) and therefore, they were not used for the accuracy assessment. The overall accuracy of the map, as well as the producer and user accuracies, was calculated using data from Table 1.

The results of these accuracies are shown in Table 2. The overall accuracy is 55%. This is less than the recommended overall accuracy of 85% (Thomlinson et al. 1999; Foody 2002). Furthermore, apart from the producer accuracy for no vegetation, all the other accuracies of the map are below 70%.

Table 1. *Revegetation map error matrix for assessing accuracy. The rows represent digitized areas from each image and the columns the field data (reference data). New veg.: New vegetation; Old veg.: Old vegetation; No veg.: No vegetation.*

		Field sampling			
		New veg.	Old veg.	No veg.	Total
Classes digitized on images	New veg.	4	3	1	8
	Old veg.	2	5	2	9
	No veg.	3	2	7	12
	Total	9	10	10	29

Table 2. *The producer accuracy is the probability that a reference land cover is well classified and the user accuracy the probability that a classified land cover on the map or image is exactly the same land cover on the ground. The overall accuracy is obtained by dividing the number of the main diagonal of the matrix by the total of the column.*

Accuracies	**Percentage (%)**
Producer accuracy for New vegetation	44
Producer accuracy for Old vegetation	50
Producer accuracy for No vegetation	70
User accuracy for New vegetation	50
User accuracy for Old vegetation	55
User accuracy for No vegetation	58
Overall accuracy	55

4.3 Estimation of revegetated areas

Revegetated areas for all SCSI activity areas in Krysuvik and for the study area were estimated and used to evaluate revegetation activities in Krysuvik and to estimate the amount of carbon sequestered through revegetation.

4.3.1 Estimation of SCSI activity inside the study area

The study area, including overlapping as well as excluding overlapping, was determined using data from the activity map of SCSI. Table 3 presents the size of treated areas and cumulative areas for study area including overlapping and the study area excluding overlapping. Figure 5 presents the cumulative area per year of the study area, both for including overlapping and excluding overlapping areas.

Cumulative areas for the study area including overlapping and the study area excluding overlapping were quite the same for 1990 to 2001. From 2002 to 2009, the cumulative area for the study area that included overlapping was larger than the one that excluded overlapping.

Table 3. *Estimation of the area size of the SCSI activity inside the study area both with and without overlapping. An overlapping area is a treated area that is counted for more than one year.*

	Excluding overlapping		Including overlapping	
Years	**Treated areas (ha)**	**Accumulated areas**	**Treated areas (ha)**	**Accumulated areas**
1990	49	49	49	49
1991	45	94	45	94
1992	60	154	60	154
1993	27	181	27	181
1994	13	194	13	194
1995	0	194	0	194
1996	0	194	0	194
1997	0	194	0	194
1998	215	401	216	410
1999	346	755	360	770
2000	0	755	0	770
2001	0	755	0	770
2002	69	824	215	985
2003	15	839	39	1024
2004	76	915	266	1290
2005	84	999	374	1664
2006	18	1017	145	1809
2007	3	1020	256	2065
2008	25	1045	52	2117
2009	1	1046	4	2121

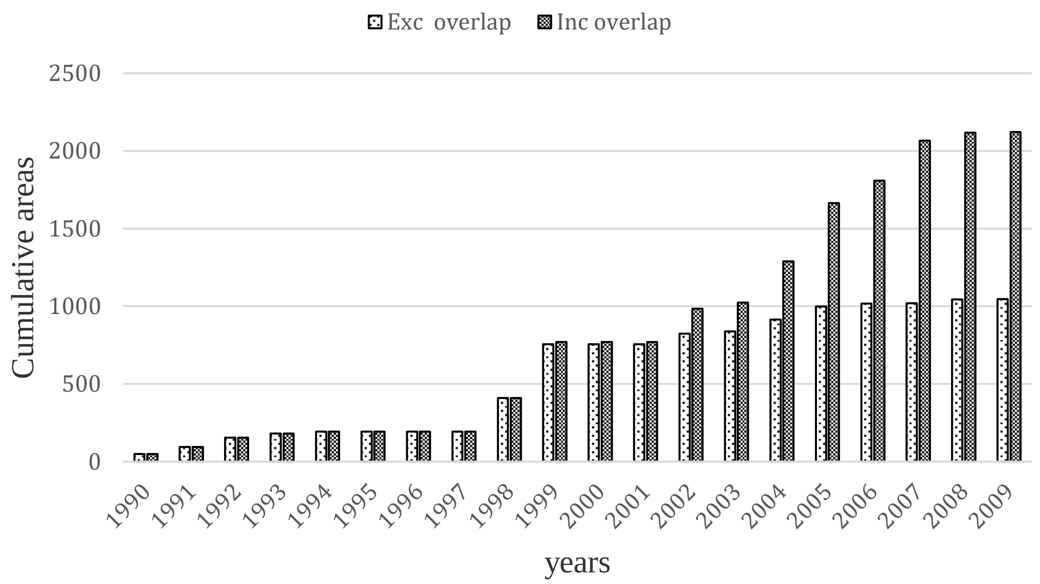

Fig. 5 *Comparison of the sizes of the SCSI activity areas inside the study area, both including and excluding overlapping areas. An overlapping area is a treated area that is counted for more than one year.*

4.3.2 Estimation of digitized areas

The size of digitized areas was estimated with and without overlapping areas. Table 4 presents areas from the three images of the study area digitized as revegetation and their cumulative areas. Digitized areas of the recent image (SPOT5) did not completely cover the digitized areas of the two earlier images. They therefore partially overlap. Figure 6 compares the cumulative areas when including overlapping areas and when excluding overlapping areas. There is little difference between the cumulative areas of digitized areas that included overlapping and those that excluded overlapping. The total SCSI revegetation activities for the study area in 2009 (1,046 ha) was obtained after summing activity for each year (Table 3). This area was significantly greater compared to the activity area of the same year obtained from digitized images, which was 286.15 ha (Table 4).

Table 4. *Digitized areas inside the study area digitized from three images from different years with and without overlapping. An overlapping area is a treated area that is counted for more than one year.*

		Overlapping excluded		Overlapping included	
Images	**Years**	**Treated areas (ha)**	**Cumulative areas (ha)**	**Treated areas (ha)**	**Cumulative areas (ha)**
L 1125	1989	16.1	16.10	16.10	16.10
M 1180	1992	28.7	44.80	31.4	47.50
SPOT 5	2009	241.35	286.15	244.83	292.33

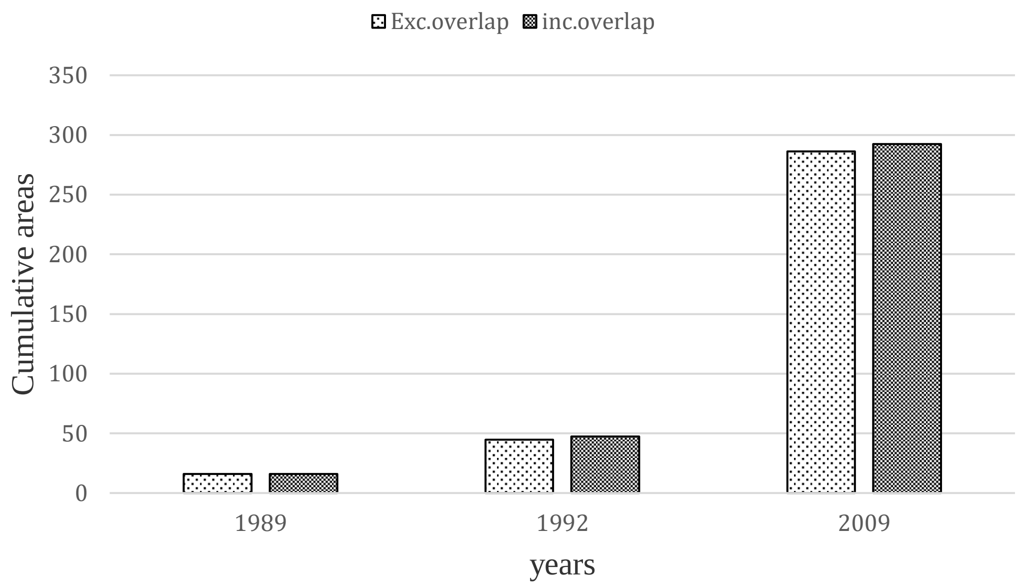

Fig. 6 *Comparison of digitized areas inside the study area, both including and excluding overlapping areas. An overlapping area is a treated area that is counted for more than one year.*

4.3.3 Estimation of all SCSI activity areas of the revegetation site in Krysuvik

Data from the activity map of the SCSI were used to estimate SCSI activity in all the area of the revegetation site. The data were determined in two different ways: both for including and excluding overlapping areas. Table 5 presents treated and cumulative areas for both all SCSI activity areas with overlapping and all SCSI activity areas excluding overlapping. The cumulative areas of all activity areas, including and excluding overlapping, are presented in Figure 7.

The cumulative area for all SCSI activity, both including and excluding overlapping, were approximately the same from 1990 to 2001. From 2002 to 2009, the cumulative area was much larger when overlapping was included than if excluded.

Table 5. *Estimation of* all SCSI activity *areas in the Krysuvik activity site with and without overlapping. An overlapping area is a treated area of a year that is counted for more than one year.*

	Overlapping excluded		**Overlapping included**	
Years	**Treated areas (ha)**	**Cumulative areas (ha)**	**Treated areas (ha)**	**Cumulative areas (ha)**
1990	49	49	49	49
1991	45	94	45	94
1992	60	154	60	154
1993	27	181	27	181
1994	13	194	13	194
1995	0	194	0	194
1996	0	194	0	194
1997	0	194	0	194
1998	238	432	238	432
1999	368	800	369	801
2000	0	800	0	801
2001	0	800	0	801
2002	369	1169	538	1339
2003	96	1265	183	1522
2004	253	1518	624	2146
2005	177	1695	733	2879
2006	50	1745	287	3166
2007	4	1749	403	3569
2008	49	1798	184	3753
2009	5	1803	68	3821

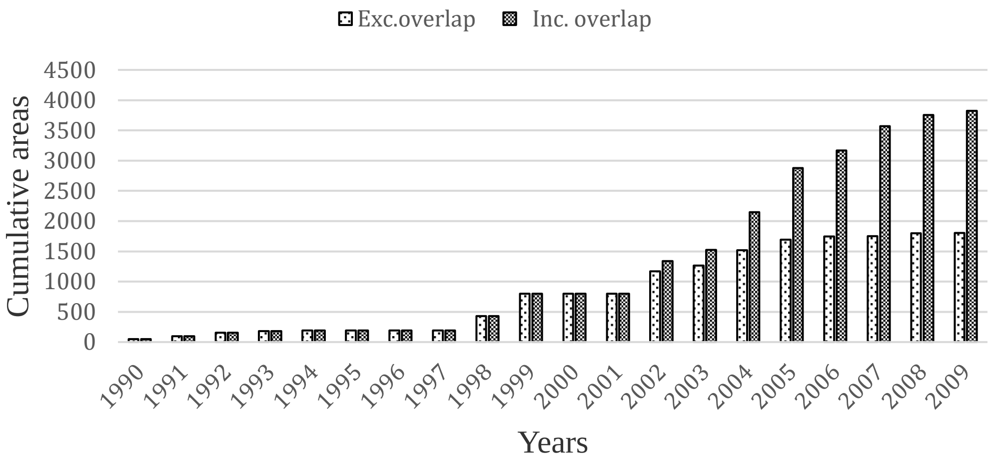

Fig. 7. *Comparison of all SCSI activity areas in the Krysuvik activity site, both including and excluding overlapping areas. An overlapping area is a treated area that is counted for more than one year.*

4.4 Estimation of carbon sequestration by revegetation actions

As stated in section 3, carbon sequestration by revegetation actions was quantified using the action areas and the emission factor of 0.57 t C/ha/yr. Carbon sequestration was estimated both for including and excluding overlapping in the study areas and in all activity areas.

4.4.1 Carbon sequestration estimation for the study area

Cumulative areas for the study area of SCSI activity were used to calculate the carbon sequestration for both the areas including and excluding overlapping. Table 6 presents the amount of carbon sequestration for each of the areas. Figure 8 presents carbon sequestration for the study area when overlapping is excluded while Figure 9 presents carbon sequestration with overlapping areas included.

Table 6. *Estimation of carbon sequestration in the SCSI activity areas inside the study area, with and without overlapping. The emission factor used was 0.57 t C/ha/yr. An overlapping area is a treated area that is counted for more than one year.*

	Excluding overlapping		**Including overlapping**	
Years	**Accumulated areas (ha)**	**Amount of carbon (t C/ha/yr)**	**Accumulated areas (ha)**	**Amount of carbon (t C/ha/yr)**
1990	49	27.93	49	27.93
1991	94	53.58	94	53.58
1992	154	87.78	154	87.78
1993	181	103.17	181	103.17
1994	194	110.58	194	110.58
1995	194	110.58	194	110.58
1996	194	110.58	194	110.58
1997	194	110.58	194	110.58
1998	401	228.57	410	233.7
1999	755	430.35	770	438.9
2000	755	430.35	770	438.9
2001	755	430.35	770	438.9
2002	824	469.68	985	561.45
2003	839	478.23	1024	583.28
2004	915	521.55	1290	735.3
2005	999	569.43	1664	948.48
2006	1017	579.69	1809	1031.13
2007	1020	581.4	2065	1177.05
2008	1045	595.65	2117	1206.69
2009	1046	596.22	2121	1208.93
Total		**6626.25**		**10 314.15**

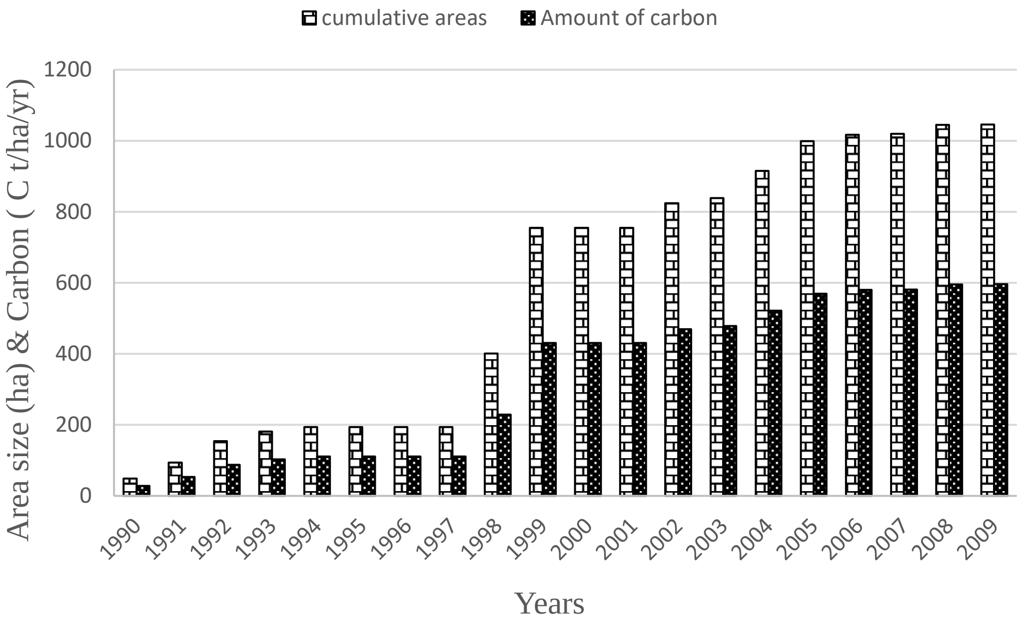

Fig. 8. *Estimation of carbon sequestration inside the study area with overlapping excluded. An overlapping area is a treated area that is counted for more than one year.*

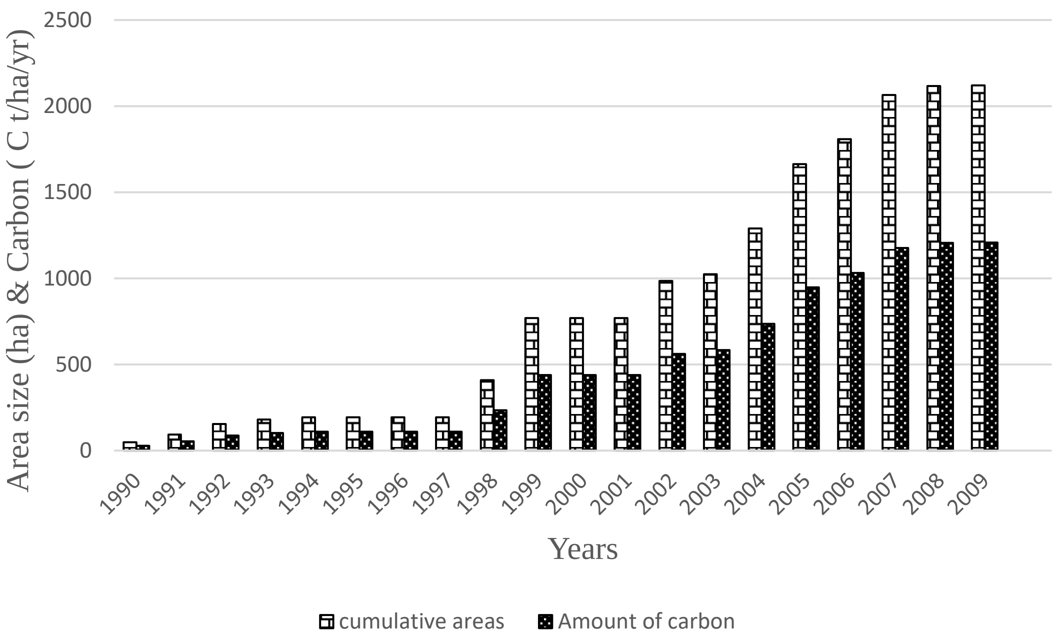

Fig. 9. *Estimation of carbon sequestration inside the study area with overlapping included. An overlapping area is a treated area that is counted for more than one year.*

4.4.2 Carbon sequestration estimation for all activity areas

The calculated amount of carbon for all SCSI activity areas, both including and excluding overlapping, are presented in Table 7.

Table 7. *Estimation of carbon sequestration in all SCSI activity areas in the Krysuvik activity site with and without overlapping. The emission factor used was 0.57 t C/ha/yr. An overlapping area is a treated area that is counted for more than one year.*

	Excluding overlapping		**Including overlapping**	
Years	**Accumulated areas (ha)**	**Amount of Carbon (t C/ha/yr)**	**Accumulated areas (ha)**	**Amount of Carbon (t C/ha/yr)**
1990	49	27.93	49	27.93
1991	94	53.58	94	53.58
1992	154	87.78	154	87.78
1993	181	103.17	181	103.17
1994	194	110.58	194	110.58
1995	194	110.58	194	110.58
1996	194	110.58	194	110.58
1997	194	110.58	194	110.58
1998	432	246.24	432	246.24
1999	800	456	801	456.57
2000	800	456	801	456.57
2001	800	456	801	456.57
2002	1169	666.33	1339	763.23
2003	1265	721.05	1522	867.54
2004	1518	865.26	2146	1223.22
2005	1695	966.15	2879	1641.03
2006	1745	994.65	3166	1804.62
2007	1749	996.93	3569	2034.33
2008	1798	1024.86	3753	2139.21
2009	1803	1027.71	3821	2177.97
Total		**9 591.96**		**14 981.88**

5. DISCUSSION

5.1 Revegetation map of the study area

The overall accuracy of the produced map (55%) is much below the minimum required accuracy (85% overall accuracy) for assessing a map (Thomlinson et al. 1999; Foody 2002). This low accuracy of the map may be the result of one of the following factors: digitizing uncertainty, errors in geometric correction of the images, the visual interpretation of the images, difference between the periods of acquisition of the images, and the field survey. But probably the large period of time between the acquisition of the images (the latest was acquired in 2009) and the realization of the field survey (carried out in 2013) and the technique of interpretation of the images which was visual may strongly have affected the accuracy of this map. The time between the acquisition of the images and the realization of the field sampling ranged from 4 to 24 years. Therefore, vegetation changes may have occurred during this long period of time within the revegetation site. This means that some vegetated areas can lose vegetation areas under grazing activities or by natural factors such as heavy rainfall. In the same way the degraded no-vegetation areas located inside fenced non-grazing areas can recover and become vegetated areas.

The technique of interpretation, which was visual, is also unsuitable for the images used in this study. It required many efforts for identification and categorisation of different land cover. For example new vegetation areas do not appear clearly on the images from 1989 and 1992. Therefore there was always a need to spend a lot of time and concentration on the images to identify and decide which areas had new vegetation. Stripped lines appeared on the

L 1125 and M1180 images which were the prints of the airplane or tractor used when fertilizing and seeding the area. For the SPOT 5 image, they appeared in red-green or pink, meaning the changing from the no-vegetated state (green colour) to the new vegetation, which is different from the old vegetation that is red in colour. Also, an error of classification may have happened, since stripped lines representing restored areas that had been digitized on the 1989 and 1992 images did not appear on the more recent SPOT 5 image of 2009. There is no complete overlapping with the recent SPOT 5 image and the two other images. Thus it is possible that stripped lines considered as restored vegetation on earlier images were just the effect of fertilizer on these images, which had been wrongly digitized as new vegetation.

Nonetheless, it should be noted that the recommended overall accuracy of 85% with no less than 70% for other accuracies (Thomlinson et al. 1999) does not meet agreement from all scientists (Foody 2002). This means that the developed map can nevertheless provide relevant information on revegetation activities in the area.

5.2 Revegetated areas

Figures 5, 6 and 7, show in general an increase in revegetation activities in Krysuvik from 1990 to 2009. In Figures 5 and 7, which were made with an SCSI activity layer map, it can be seen that the revegetation activity in Krysuvik started to increase significantly around 2001-2002. This can be explained by an increase in interest in Iceland during this period for carbon sequestration through revegetation, since the country had ratified the Kyoto protocol during the same period (23rd May 2002). Recording in real time of most revegetation activity since 2002 (Environment Agency of Iceland 2013), may also account for the observed increase from 2001-2002 to 2009. GPS records can be more accurate and conserved for a long time compared to the traditional way of documenting activities on paper.

A difference between areas including overlapping and areas excluding overlapping can also be observed in Figures 5, 6 and 7. The areas estimated with overlapping included are much bigger than the ones estimated without overlapping. For example, the accumulated area in 2009 for the study area with overlapping is 2121 ha whereas it is 1046 ha without overlapping. Also, the cumulative area in 2009 for the digitized areas with overlapping is 292.33 ha whereas without overlapping it is only 286.15 ha. In estimating revegetation activity areas, if overlapping areas are not excluded some portions of the activity area may be counted twice and consequently bias the estimate of the revegetated area.

The comparison between the SCSI activity area inside the study area and the digitized area also show a difference in size. The cumulative SCSI activity areas of the study area excluding overlapping covers 1046 ha (Table 3) while the cumulative area for the digitized area excluding overlapping comes to 286.15 ha (Table 4). The difference between these two areas gives a difference of 759.85 ha, which should normally not be since both areas represent revegetation activities of the SCSI from 1990 to 2009. This difference can be explained by the fact that old vegetation was treated in some parts and accounted for by the SCSI when recording revegetation or it can have been because of a failure in digitizing activity areas with the use of the images during the study. Only new vegetation has been identified and digitized on the images because overlaps and omissions should be avoided when estimating land area. In recording and reporting revegetation activity, care must be taken to avoid counting old vegetation with new vegetation because this may wrongly increase the size of the areas to be reported as revegetation sites.

5.3 Carbon sequestration and overlapping areas

There was an increase in carbon sequestration with the increase in area and this can be observed in Figures 8 and 9. In Table 6 (for the SCSI activity inside the study area) and Table 7 (SCSI all activity area) it can be seen that there was an increase in the carbon sequestration rate with increase in area size. Therefore, with overlapping which increases land area (meaning that some portion of the area is counted twice), the carbon sequestration amount increased as well (Tables 6 and 7). Carbon sequestration with overlapping came to 10314.15 t C/ha/yr for the SCSI activity inside the study area and 14981.88 t C/ha/yr for all SCSI activity area. These rates are much greater than the rate of carbon sequestration of the same areas when overlapping is excluded, which are respectively 6626.25 t C/ha/yr and 9591.96 t C/ha/yr.

6. CONCLUSION

The following conclusions were drawn from this study:

- Development of a low accuracy map that can be used for monitoring of revegetation in Krysuvik
- The size of the SCSI activity areas inside the study area were shown to be larger than those obtained from digitized areas
- The size of areas estimated with overlapping were shown to be greater than the area sizes estimated without overlapping
- Areas with overlapping were shown to have had higher amount of carbon sequestration than areas without overlapping.

Revegetation activities should therefore be recorded without overlapping and old vegetation to avoid overestimating the size of activity areas and the actual amount of carbon sequestration.

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