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Spectral response of forest disturbances induced by beaver-caused floods: A case study of Estonia using Sentinel-2 MSI image time series

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Abstract

Beavers are known as ecosystem engineers and the habitats that they create can change the landscape greatly. When a new beaver colony establishes itself by building dams, digging canals and burrows and felling trees, the resulting changes are often large enough to be studied with medium resolution earth observation sensors like Sentinel-2 MSI. In this study we compare the spectral signatures of 405 sample areas disturbed by beaver-induced flooding with 261 healthy forest sample areas surrounding the area. We used 28 Sentinel-2 MSI multispectral images from years 2015 to 2018 over the southern part of Estonia in Military Grid Reference System map tile T35VME. In summer the average pixel values for areas that are affected by beavers show the largest differences in reflectance values for shortwave infrared (SWIR) and the visible parts of the spectrum compared to areas that are not affected by beavers. Some smaller differences are present also in the near-infrared (NIR) parts of the spectrum, but sometimes they are not significant according to *p*-values, being over the 0.05 threshold, of the *t*-test. In autumn and spring, when deciduous trees do not have their leaves and ground vegetation is not thriving, the differences in visible parts of the spectrum disappear. Multispectral vegetation indices, like the Normalized Difference Vegetation Index (NDVI) and others, also show clear differences in the beaver-disturbed forests and surrounding healthy forests throughout all vegetation phenology stages.

Keywords: beavers; flood disturbance; phenology; forest damage; habitat change; Sentinel-2 MSI

Introduction

Eurasian beavers (*Castor fiber* L.) are one of the largest rodents in the world and the largest ones in Europe. They were once widespread all over Europe then hunted to near extinction but have made a remarkable recovery in population and distribution all over Europe. Reintroductions all over Europe have re-established beavers to the landscape (Halley et al. 2012). For current time, beaver populations in Europe have reached numbers beyond the point when the loss of genetic diversity would be a conservation problem. In the Republic of Mordovia (Russian Federation) in Eastern Europe (Andreychev 2017) there are on average 0.52 beaver colonies per kilometre of river, and they are present in many of the river basins, lakes, and ponds. In Estonia beavers were wiped out as a result of overhunting in the middle of the XIX century and were reintroduced in 1957 (Laanetu 1992). Only in a period of a few decades the beaver population has risen dramatically with the highest estimated population reaching 15,000–20,000 specimens in Estonia in 2001. Now hunters are controlling the beaver population to keep it at the level between 3,000 to 13,000 animals in Estonia (Keskkonnaamet 2021).

Beavers have the ability to intentionally modify their environment by building dams and thus they are called natural ecosystem engineers. The dams can provide natural flood management barriers and be used to support renaturalization of rivers establishing habitat to many species (Gaywood 2018) and renaturalize artificially homogenized river reaches (Gorczyca et al. 2018).

On average, one beaver family has 4 members with one breeding pair (Halley et al. 2012). Beavers construct and rebuild the dams fast when destroyed by humans. An average family of 4 individuals will start rebuilding activities on average 2 days after dam destruction but almost immediately in autumn time. Larger families start rebuilding faster. A family of 4 beavers can completely rebuild a destroyed dam in a day (Raškauskaitė and Šimkevičius 2017). Eurasian beavers can live in various habitats, but they prefer riverine willow shrubs and poplar forests. If river conditions are suitable then ash-alder alluvial forests and lowland river hardwood forests are also preferred by the beavers over other forest types (John and Kostkan 2009).

The impact that beaver habitats can impose on the ecosystem depends greatly on their geographical location. The relief of the land, the habitat type, and beaver population size have a large impact on the resulting changes that beavers make on the landscape. Ecosystem engineers like beavers can provide habitats to many other species. Many amphibians can use the habitat associated with beaver dams as a breeding location. However, the landscape changes that beavers make harm some species (Rosell et al. 2005). Beavers also have a significant impact on the sediment and nutrient storage related to their dams slowing the stream and gathering material coming from upstream (Puttock et al. 2018).

In forested wetland areas disturbances can decimate the existing trees and other vegetation. Typical mesic forested vegetation species are replaced by hydric species over time (Mitchell and Niering 1993). Grey alder (*Alnus incana* L.) can show significant water stress in the first year of flooding while other species like willows show only slight changes in foliage colours. In the second and third years of persistent flooding, the conditions of all trees start to worsen, and birches and black alder trees lose almost all their foliage. The willows are more resistant and can survive longer. Macrophyte species composition does not change very rapidly in response to beaver-induced flooding, but species response varies when some plants gradually disappear and others thrive (Nummi 1989). Beavers also eat vascular aquatic plants selectively and this can increase species richness by reducing the abundance of otherwise dominant species (Law et al. 2014).

The satellite imagery and aerial photographs have been used for beaver mapping for a long time. Common way to map beavers is to use visual interpretation of areal images or high spatial resolution satellite data. One of the earliest uses of this technique was reported by Parsons and Brown (1978) who were using aerial photographs. Johnston and Naiman (1990) used the same visual interpretation technique on aerial photos to map beavers, and later Meentemeyer and Butler (1995) assessed beaver geographic distribution and temporal characteristics using the same visual mapping from photographs. Nowadays similar simple visual interpretation of beaver impacts on the landscape is also used with high resolution satellite data by Herrera et al. (2020). Besides visual interpretation, unsupervised classification algorithms were used on Landsat MSS (Multispectral Scanner) data by Finn and Howard (1981) to show that it is feasible to use multispectral satellite data for the disturbance detection. More recently, supervised machine learning algorithms have been implemented to detect beavers expanding in Alaska and north-western Canada (Tape et al. 2018) and in Massachusetts (Pasquarella 2016). Both of these studies relied on calculated multispectral vegetation indices from satellite data to aid in beaver-induced change detection.

In case of beaver-caused disturbances, the spectral signature of forests is also influenced by the change of optical properties of ground vegetation and soil that can be covered by water. Reflectance spectra of healthy leaves of boreal tree species are published by Hovi et al. (2017). Studies of the influence of waterlogging on leaf optical properties are hard to find but Croeser et al. (2021) showing in their study that in case of fortnightly 24 hours waterlogging marri trees have increased absorption in the visible and SWIR parts of the spectrum. Combined effects of flooding and tree root pathogens cause finally damage to photosynthetic apparatus in the marri leaves (Croeser et al. 2021). Other types of damage can also change the spectral characteristics of the trees. Abdullah et al. (2019) compared a forest disturbed by bark beetle (*Ips typographus* L.) to healthy forests and found that the red-edge and shortwave infrared (SWIR) bands were very useful for separating between healthy and infested plots and this difference was present in all stages of disturbance. For the bark beetle-disturbed forests the changes became apparent in the visible spectrum, from 680 to 790 nm, and the shortwave infrared, from 1,110–1,490 nm, as the damage progressed. When looked in a time series, a temporal variation was present in both reflectance values and calculated indices (Abdullah et al. 2019).

Studying the deeper mechanisms and the spectral signature of beaver-impacted area could be helpful for remote sensing purposes. In this study we compare the impacts of beaver habitats on forested areas to healthy forests surrounding the disturbance locations. As tree species have different spectral characteristics, the impact of beaver-induced disturbance in the forest was studied with tree species composition in mind. Phenology of the vegetation varies largely throughout the year and thus different seasonal effects were also taken into account in this study.

Materials and methods

Study area and the field observation data

The observations of beaver habitats in Estonia within the Military Grid Reference System map tile T35VME were used (Figure 1). This area had the highest density of beavers discovered during the official survey in Estonia (Veeroja and Männil 2016). The data about beaver habitat locations was provided by the Estonian Environment Agency. The beaver habitats are counted regularly by hunters and volunteers (Keskkonnaminister 2013).

Description of typical beaver-induced disturbances on forest

Beavers create very heterogeneous habitats. When a beaver colony dams a stream, the effects from the resulting flooding can vary greatly depending on the topography of the site. Often the rise of water level is contained in a high walled drainage ditch and no pond is formed.

The typical beaver habitats vary in their appearance depending on the age of the beaver pond. Recently established habitats (up to 1-year-old) still have living trees trying to survive inside the newly formed pond, but trees

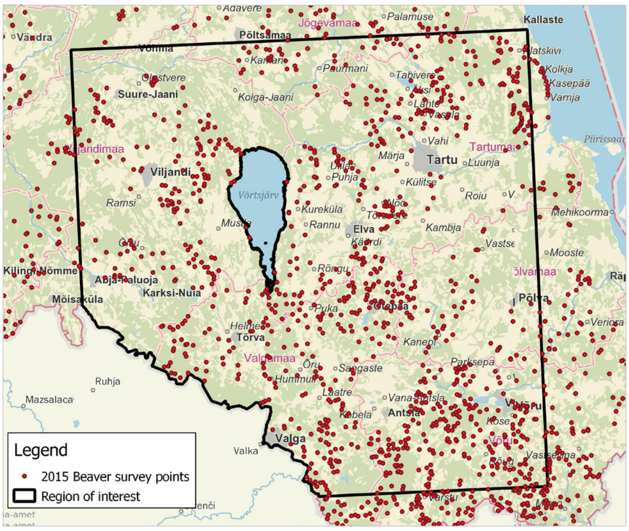

Figure 1. Map of the study area in the southern part of Estonia. Background map is obtained from the Estonian Land Board (2021)

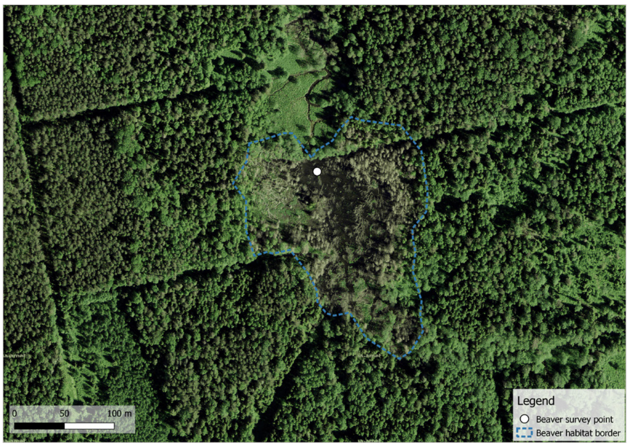

Figure 2. An example of a typical beaver habitat viewed from an aerial photograph (Maa-amet 2015) in summer of 2015

show significant stress signs due to lack of oxygen in the soil for root respiration. There are some individual trees that have been felled by the beavers or have fallen over on their own due to softening and erosion of the soil. The previous ground vegetation that is now partly or entirely covered by water is dead or dying, however, some wetland vegetation plants might be already starting to establish and even dominate in patches.

Most of the trees are dead within the flood area within established habitat ponds during 2–4 years. Often the flooded pond has tree trunks sticking out of it sometimes with dead branches still attached or broken off and fallen to the ground and water. On the banks of the pond, the trees usually show several signs of stress related to the raise in the water table depth in the soil. Beavers also fell trees on the pond banks where water stipulates their access. Along the bank and through shallow water, beavers dig canals and burrows. As viewed from above, one can notice a gradual decline of disturbance to the trees beginning with the pond centre towards its banks (Figure 2). The previous ground vegetation is usually replaced inside the habitat with more typical wetland vegetation as seen in Figure 3.

Over 5-year-old habitats usually do not have any living trees left in the pond area, there might be tree trunks lying on the ground and still decaying. Depending on the depth of water in the dammed area the pond might not have any open water at this point as wetland vegetation often covers the whole area. If the beavers are still active, the ditches and burrows are maintained and visible on site. In some cases, beavers have gradually raised the water level by expanding the dam to lead water farther towards new trees for consumption.

Figure 3 shows a typical result after water level rise caused by beavers is the death of trees. This image illustrates an example where the dead trunks are still standing, and the area is surrounded by still living trees growing on higher ground that is not influenced by the flood. The surrounding trees are alive but on some trees that are closest to the flooding the signs of stress can be noticed on the canopy. In the scene there are visible areas with open water and tree trunks lying on the ground. The ground vegetation is typical to a marshland and dominated by tufts of some *Carex* genus and *Typha latifolia*. These plants have spread wider from the original stream edge due to the flooding and replaced the vegetation growing there that previously was adapted for dryer conditions.

Forest mortality increases substantially after beaver-caused flooding (Figure 3). In Figure 4a there is an area, where beavers established a habitat in 2015 and in the late summer of 2017, the area was substantially changed as detectable also from the orthophotos. The habitat was fully flooded and open water covered the patch. Some trees have fallen over, and others are left standing but may have parts of their branches or trunks broken.

Over the flooded area the NDVI values are substantially decreased and smaller compared to ones of the surrounding forest and grasslands (Figure 4b). In the middle of the beaver habitat area the NDVI value is around 0.45, the surrounding healthy forest has a value around 0.80 and the grassy land has NDVI value around 0.85.

Figure 3. An example of a typical beaver habitat. The photo was taken on 25.08.2019 at geographic coordinates 57°59'12"N 26°03'30"E

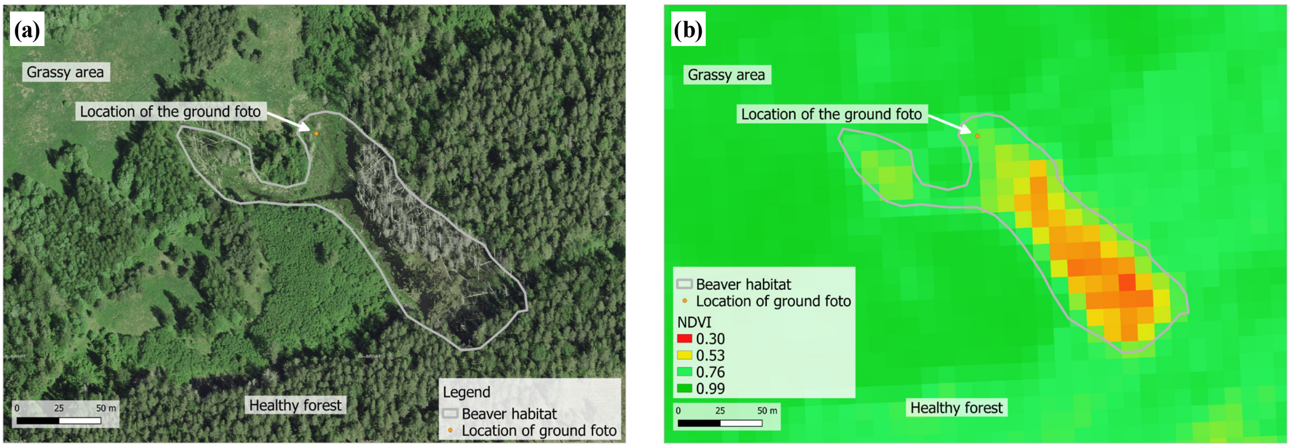

Figure 4. (a) Orthophoto (Maa-amet 2017) of a 2-year-old beaver habitat and its surrounding area as shown in Figure 3. **(b)** Normalized difference vegetation index (NDVI) of the area as calculated from the Sentinel-2 MSI image taken on 30.08.2017

Construction of a map of beaver habitat areas

The data used in this paper was collected during the 2015 beaver habitat counting. The counting data indicated habitat locations as points (coordinate system EPSG:3301) around which we manually digitized beaver habitat polygons based on visual interpretation of regular (RGB) (years 2014, 2015 and 2017) and false colours (CIR) (years 2013 and 2017) aerial photographs provided by the Estonian Land Board. Where visible disturbance to the trees and the vegetation near a beaver location point was spotted, the area was marked as a polygon. This kind of visual classification of beaver habitat areas, using aerial photographs, or other high spatial resolution images, has been used previously to identify beaver habitats (Parsons and Brown 1978, Johnston and Naiman 1990, Meentemeyer and Butler 1995, Herrera et al. 2020). Only the areas that were most clearly and undeniably influenced by beaver activity were selected for this study. Areas where the dam has been destroyed or the beaver activity has no flooding effect to the forest were excluded. Also, the beaver habitat area had to be outside of natural lakes and rivers where beavers do not cause flooding. An area had to be large enough to fully contain at least 10 Sentinel-2 MSI 10-meter pixels to be considered suitable for the analysis. These criteria narrowed the list of suitable examples and in this study we could finally observe 376 habitats.

Forest inventory data

In order to obtain information about the tree species composition for the 376 habitat areas, the database of the Estonian Forest Register from year 2013 was used. Forest stand borders were used to divide the habitat areas to subsections according to forest stands. The forest stands intersecting the beaver habitat areas were divided into two classes: (1) affected by beavers (ABB), and (2) non-affected by beavers (NABB). The aim was to obtain two comparable sets in respect to forest inventory variables. Forest stands bordering the disturbed area that did not have any signs of beaver-induced disturbance were excluded from the analysis to keep the ABB and NABB samples comparable considering the distribution of tree species and the age of the forest stands (Figure 5). If a forest stand extended over both the ABB and NABB areas the stand polygon was split into two classes. Also, sometimes the flooding covered the forest stand entirely thus there was no option to obtain data for not affected area for that stand. All these criteria combined resulted in a different count of total sample areas for the ABB and NABB samples, 405 and 261, respectively. Within these samples we mainly looked at the stands that have one dominant tree species representing at least 75% of the stand basal area. Two general groups of stands were constructed as deciduous and coniferous forests, where the stands had a combined dominance of deciduous or coniferous trees over 75% of all tree species. The most numerous are the birch forests followed by pine forests (Table 1).

Table 1. Distribution of the samples according to the dominant tree species (more than 75% of basal area)

Dominant tree species	Affected by beavers		Not affected by beavers	
	count	total area (ha)	count	total area (ha)
Birch (*Betula pendula* Roth)	75	53.5	47	32.7
Aspen (*Populus tremula* L.)	12	6.0	9	14.1
Spruce (*Picea abies* (L.) H. Karst)	30	16.4	20	21.7
Pine (*Pinus sylvestris* L.)	54	51.3	32	34.1
Black alder (*Alnus glutinosa* (L.) Gaertn)	3	1.6	0	0.0
Grey alder (*Alnus incana* (L.) Moench)	14	11.7	10	7.0
Deciduous broadleaved	168	126.9	107	99.2
Coniferous evergreen	113	93.1	65	69.2

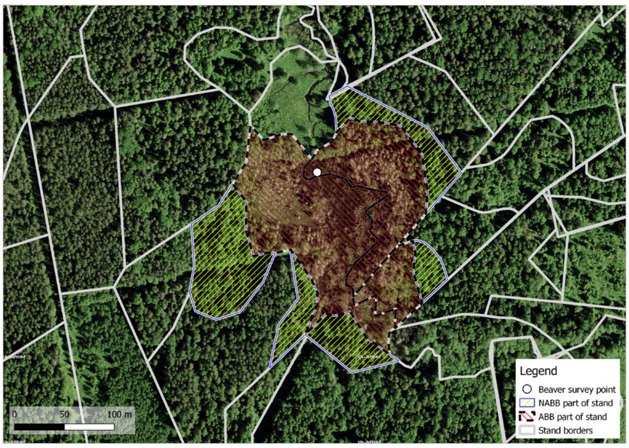

Figure 5. An example of how the beaver habitat area and the surrounding forest stands were split into the sample polygons. NABB indicates the parts of a stands that are not affected by beavers and ABB stands for areas affected by flooding. Background photo is provided by the Estonian Land Board (Maa-amet 2015)

Image analysis

A set of Sentinel-2 MSI images was downloaded from ESA's SciHUB. These images covered all the Military Grid Reference System tile T35VME. The image dates start from summer of 2015 and end with autumn 2018 (Table 2). No further dates were looked at due to the ground truth data being from 2015.

The surface reflectance data, i.e. processing level L2A (ESA 2021b), was chosen. If from the selected date L2A-level processing data was not available from ESA's SciHub then L1C (top of atmosphere radiance) level image was downloaded and processed to L2A with sen2cor processor (ESA 2021a) in SNAP (version 6.0.0) (SNAP Team 2018) with default parameters taken from the image metadata. The images were then resampled to 10 m resolution and projected to the Estonian base map coordinate system (EPSG:3301). For the analysis the following spectral indices were calculated in QGIS (ver. 3.4) (QGIS 2018) for each pixel with formulas for:

$$NDVI = (B08 - B04) / (B08 + B04) , \quad (1)$$

$$NDMI = (B08 - B11) / (B08 + B11) , \quad (2)$$

$$NDWI = (B03 - B08) / (B03 + B08) , \quad (3)$$

$$VMSI = B11 / B08 , \quad (4)$$

were Bxx stands for the Sentinel-2 MSI bands with central wavelengths B03 (559.8 nm), B04 (664.6 nm), B08 (832.8 nm), B11 (1613.7 nm) and NDVI stands for Normalized Difference Vegetation Index, NDMI stands for Normalized Difference Moisture Index, NDWI stands for Normalized Difference Water Index, and VMSI stands for Vegetation Moisture Stress Index. Then the average pixel values of each vegetation index image over each ABB or NABB area were calculated using the raster layer zonal statistics processor in QGIS (version 3.4) (QGIS 2018). We observed that the coefficient of variation (calculated by dividing the mean pixel value for each sample area by

Table 2. The Sentinel-2 MSI images used in analysis with information about the seasonal and weather conditions during acquisition and usable beaver habitat samples for evaluation as ABB (affected by beavers) and NABB (non-affected by beavers) within coverage

Date	Season	Cloud cover	Tile coverage	Count	
				ABB	NABB
04.08.2015	summer	almost cloudless	full	401	256
07.08.2015	summer	partly cloudy	corner only	9	8
24.08.2015	summer	partly cloudy	full	242	174
03.10.2015	autumn	cloudless	full	405	261
07.04.2016	early spring	partly cloudy	corner missing	329	216
27.04.2016	spring	partly cloudy	corner missing	382	244
07.05.2016	spring	cloudless	corner missing	401	261
28.08.2016	summer	partly cloudy	full	373	240
02.05.2017	spring	cloudless	corner missing	405	261
30.08.2017	summer	minimal clouds	corner missing	405	261
22.10.2017	autumn	partly cloudy	full	347	224
12.04.2018	early spring	partly cloudy	corner missing	335	220
07.05.2018	spring	minimal clouds	corner missing	404	261
10.05.2018	spring	cloudless	full	405	261
12.05.2018	spring	cloudless	corner missing	405	261
20.05.2018	late spring	partly cloudy	full	372	246
25.05.2018	early summer	partly cloudy	full	402	254
27.05.2018	early summer	partly cloudy	corner missing	367	235
30.05.2018	early summer	partly cloudy	full	401	257
01.06.2018	early summer	partly cloudy	corner missing	394	258
09.06.2018	early summer	partly cloudy	full	376	232
10.08.2018	summer	partly cloudy	corner missing	286	194
23.08.2018	summer	minimal clouds	full	405	261
19.09.2018	late summer	cloudless	corner missing	405	261
12.10.2018	autumn	partly cloudy	corner missing	344	222
14.10.2018	autumn	cloudless but hazy	corner missing	405	261
17.10.2018	autumn	cloudless but hazy	full	405	261
19.10.2018	autumn	cloudless	corner missing	405	261

its standard deviation and multiplying by 100) in all bands was relatively high due to the high heterogeneity of the sample areas. For example, in the image dated 04.08.2015 in Sentinel-2 MSI blue band (B02) 90-percentile of the coefficient of variation was larger than 9.9 for the ABB areas and larger than 13.8 for the NABB areas for all samples. The number of pixels in each sample polygon was recorded to account as weight of each sample area. The rest of the data analysis was done in RStudio (version 1.4.1103) (RStudio Team 2021).

Results

Reflectance changes in the spectral bands

During the vegetation period the mean spectral signature of the forest stands or their parts located on the undisturbed areas had the characteristic shape of healthy vegetation (Figures 6, 7 and 8). The smallest reflectance in summertime images was found in the bands in the visible part of electromagnetic spectrum (B02; B03; B04). Reflectance in green band (B03) was typically higher than in other bands of visible part of the spectrum. The highest reflectance was present in the NIR bands (B08 and B08A) reaching values of almost 0.40. Reflectance in the SWIR bands (B11 and B12) was greater than in the visible bands.

The influence of beaver-caused disturbances changed pixel values in all Sentinel-2 MSI bands. For example, the results presented in Figure 6 show that in birch-dominated forests a clear rise in reflectance was present in the visible bands and in the first red edge band (B05) for the ABB areas in late summer 2015. In the near infrared (B08 and B08A) bands the ABB areas have a smaller reflectance, but the variation of the signal across different beaver colonies is less compared to the birch forest that are not affected by the flooding. In the shortwave infrared bands the NABB areas have again a clearly smaller reflectance than the ABB areas. Two-tailed *t*-test shows that most of these differences are significant except for B11 (*p*-value of 0.131) and for the last red edge band B06 (*p*-value of 0.052).

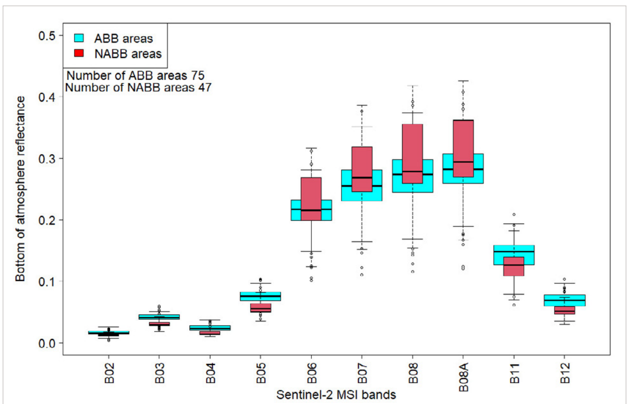

Figure 6. The boxplot of the average ABB (affected by beavers) and NABB (non-affected by beavers) top of canopy reflectance over the birch-dominated samples in a summertime image dated 04.08.2015

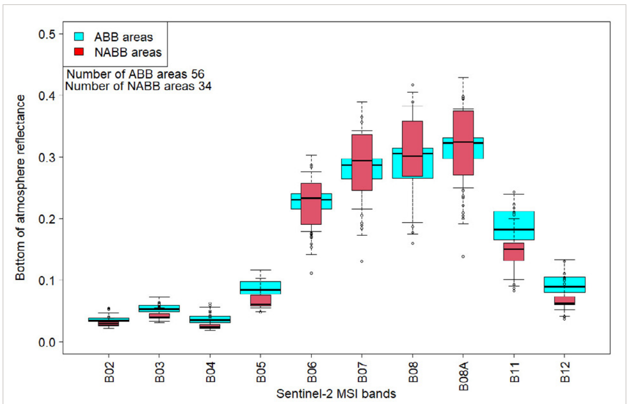

Figure 7. The boxplot of the ABB (affected by beavers) and NABB (non-affected by beavers) top of canopy reflectance over the pine-dominated samples in a summertime image dated 04.08.2015

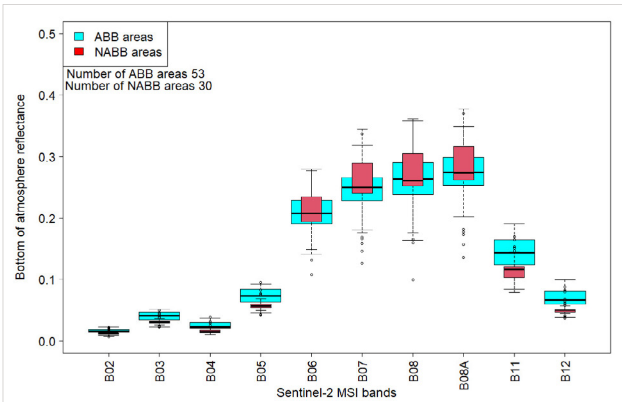

Figure 8. The boxplot of the average ABB (affected by beavers) and NABB (non-affected by beavers) top of canopy reflectance over birch-dominated samples in a summertime image dated 10.08.2018

In Scots pine-dominated stands (Figure 7), the reflectance changes were similar to the birch forests in the visible and SWIR bands. In both spectral regions the reflectance of the ABB areas was greater than those of the NABB areas. The differences between the ABB and NABB areas in the NIR bands are small and not significant according to the *t*-test.

In the summer of 2018 (Figure 8), the difference in the NIR band between the ABB and NABB areas has practically disappeared compared to the image dated August 2015 (Figure 6). For example, in band B08 the t-test for difference yielded *p*-value of 0.502. This may be due to the fact that 2018 was a very heat and dry year with a previous month (prior to image acquisition on 10.08.2018) having an average rainfall of 26 mm (with normal being 72 mm) and an average temperature of 19.9°C (normal average 17.4°C) (Riigi Ilmateenistus 2021a) and especially in the days before the 10.08.2018 image acquisition there was almost no rain but hot temperatures (around 30°C)

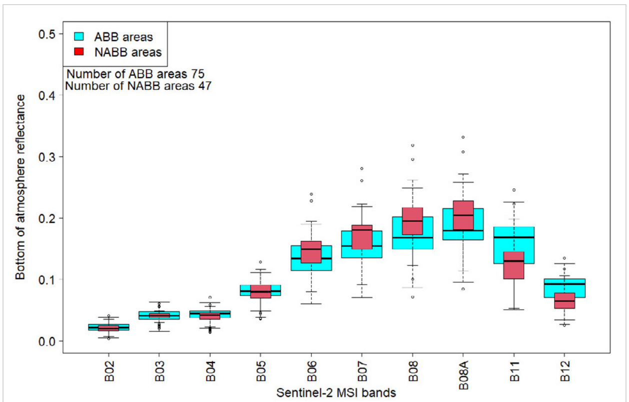

Figure 9. The boxplot of the average ABB (affected by beavers) and NABB (non-affected by beavers) top of canopy reflectance over the birch-dominated samples on 14.10.2018 during autumn leaf fall

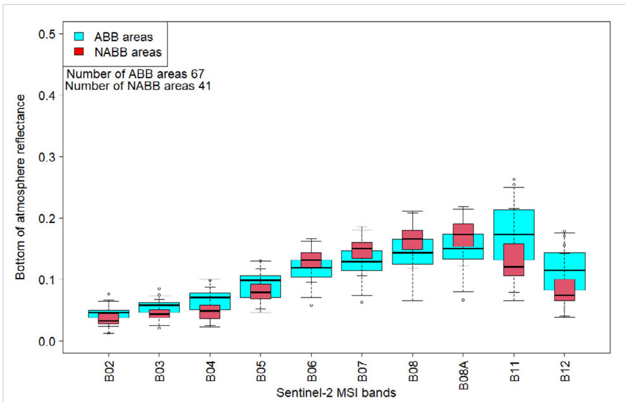

Figure 10. The boxplot of the average ABB (affected by beavers) and NABB (not affected by beavers) top of canopy reflectance over the birch-dominated samples in spring (image data 07.04.2016) before leaf unfolding

lasted over a week (Riigi Ilmateenistus 2021b). Whereas, in 2015, during the days before image data 04.08.2015, there was recent rainfall all over Estonia for several days (Riigi Ilmateenistus 2021b). Also as the dynamic nature of beaver habitats can change the landscape somewhat in 3 years, the differences between Figure 6 and Figure 8 may be due to natural development.

In the birch forests, in autumn, image data 14.10.2018 (Figure 9), we can note that the difference in the visible bands is not there anymore for the ABB and NABB areas (t-test p-values range from 0.47 to 0.92). This is probably due to the phonological stage of the vegetation. The higher reflectance of the NABB areas in the NIR and B06 and B07 bands in the red edge part of the spectrum remains (t-test p-values from 0.004 to 0.039).

In early spring image dated 07.04.2016, the differences between the ABB and NABB samples in the visible and SWIR spectra are not significant (p-value > 0.1) but the difference in the NIR band remains (p-value < 0.0001) (Figure 10). In general, the spectral signatures in early spring are similar to that of autumn with much smaller difference in the visible and NIR spectra compared to summertime. As the foliage develops with starting the vegetation period, the differences in spectral bands become more distinct as shown in previous figures (Figures 6 and 8) that present the spectral differences in the summertime when vegetation has full foliage.

The time series of multispectral indices

The NDVI time series of evergreen coniferous stands and deciduous stands were similar (Figures 11 and 12). In summer the NDVI values are higher than in spring or autumn. From early to late spring a steady increase of the NDVI values is evident. In autumn the NDVI values decrease as vegetation loses leaf cover and therefore also chlorophyll that are the two influencing factors for NDVI.

The trends from season to season exist in both types of forests and the NABB areas have consistently higher NDVI values. The difference is significant in each image with t-test p-values all being under 10^{-5} with one

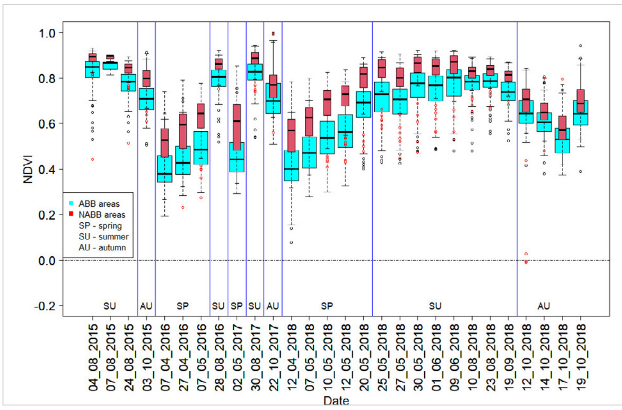

Figure 11. The boxplot of average NDVI values over the deciduous broadleaved forests in the ABB (affected by beavers) and NABB (not affected by beavers) areas for all Sentinel-2 MSI images taken at different phenological stages

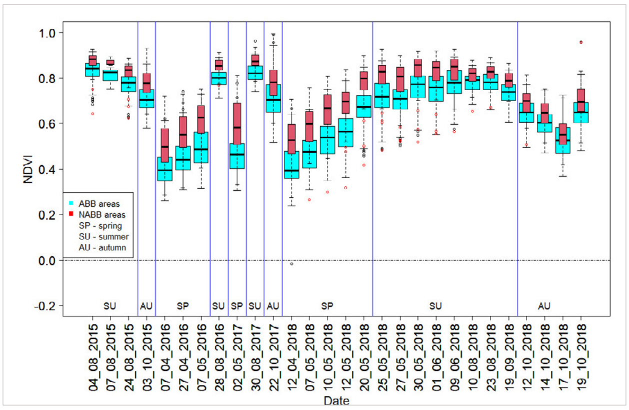

Figure 12. The boxplot of average NDVI values over the coniferous evergreen forests in the ABB (affected by beavers) and NABB (non-affected by beavers) areas for all Sentinel-2 MSI images taken at different phenological stages

exception being on the image dated 07.08.2015 with few samples only (Table 1). The greater NDVI values over the NABB areas compared to the ABB areas are present in all images regardless of the phenological stage. Also, other indices like VMSI, NDMI, and NDWI have very strong difference between the ABB and NABB areas (Appendix A).

Discussion

For the interpretation of spectral signatures recorded over the sites with flood disturbance some healthy forest data have to be brought for comparison. According to Rautiainen et al. (2009), in healthy birch forests in Estonia the green and SWIR parts of the spectrum have relatively stable seasonal reflectance dynamics, but the red and near-infrared (NIR) parts of the spectrum reflect the seasonal phenology of the total stand leaf area, chlorophyll, and water content. Concerning different soil types of the growing sites, the start of seasonal growth has dependent time lag in spring. Comparing forest stands growing on fertile and infertile soils the development may be offset by twenty days (Rautiainen et al. 2009).

The forest understory vegetation can also play an important role in contributing to the total forest reflectance according to Pisek et al. (2015), and Rautiainen and Lukeš (2015). In boreal forests the understory contribution to forest reflectance is the highest in the visible part of the spectrum and drops at the red-edge and stays low in the near infrared parts. During the growing season the NIR contribution stays relatively the same, but the visible part of the spectrum shows greater changes throughout the year.

The differences of the ABB and NABB areas depend on the weather prior the satellite image acquisition and phenology. Different years may have different spectral signatures around the same dates. The analysis shows that there are always at least certain spectral bands that show a significant difference in the reflectance, but it may not be consistent from year to year as the weather conditions, water availability, and phenology play a significant role in reflectance values for these areas.

When comparing deciduous and evergreen forests we see similar trends over the ABB areas with regards to the spectral signatures (Figures 6 and 7) or when looking at the NDVI series (Figures 11 and 12). This may be due to the fact that the trees are dead or dying in both samples and the main influencing factor of the reflectance has become the forest stand background, exposed bare soil, abundant dead organic plant material, and water instead of the tree leaves or needles. The remaining 25% of broadleaf deciduous trees or evergreen coniferous trees in the two general classes may have an influence as well; because in this study the deciduous and coniferous forests are classified as such at 75% of deciduous or coniferous trees present in the stand. The remaining mixed forest part may also influence the average values.

When we compare the early spring and late autumn (Figures 9 and 10), it appears that in the visible spectral bands the average reflectance difference between the ABB and NABB areas is small. This is most probably due to the vegetation phenology. In both time periods only the evergreen coniferous trees have foliage, whereas most of the ground vegetation is withering or dead. This is leaving us only with the water-related parts of the spectral signatures to focus on. On the other hand, in the summer we can see a big difference in the bands that are influenced by chlorophyll absorption and leaf area index. The mortality in the flooded areas or waterlogged soil is substantially increased due to severe stress on the trees and undergrowth, thus changing the spectral reflectance.

There are also some trees felled by the beavers themselves for the use as building materials for their dams and lodges and for food. These trees are usually on the banks of the flooded area and not in the water. Beavers create complex earthworks for their habitats. They dig tunnels and burrows on the shores of their newly constructed ponds. These are for easier movement and transport of the branches and logs. These earthworks on the banks can also propagate the waterlogging effect of the soil further inland providing a sort of irrigation canal system. The resulting heterogeneity of the land increases the variability of spectral signatures, from pixel to pixel, even within one pond around one beaver colony. The spatial resolution of Sentinel-2 MSI pixel is 10–20 meters and this makes it difficult to capture this variation within the relatively small beaver habitats.

We found that the change in forest spectral signature can be used to detect beaver habitats. Our results show that there are rather distinct differences between disturbed and undisturbed areas and therefore machine learning could be used to detect beaver habitats over large areas quite effectively. Using the selected bands from a spectral signature as well as the common vegetation indices a predictive model can be constructed.

Early detection of beaver habitats is important for decision making in places where flooding causes direct economic losses for the forest owner. Machine learning-based applications can be developed if a training sample library is available. In case of beaver habitat detection such application requires also masks for water bodies, ditches and streams for better targeting the analysis. The training set can be compiled based on field observations; however, this source alone may not be sufficient to collect enough samples. Radiative transfer models may be useful to extend the training set library (Wolanin et al. 2019). Incorporation of a forest radiative transfer model like FRT (Kuusk and Nilson 2000) also helps unmixing the factors that influence the forest spectral signature regarding the evolution of beaver habitats. The changes in the canopy and the undergrowth caused by beavers can be modelled to get simulated data for the reflectance changes with time across the spectrum. As the response functions of satellite scanners are published in corresponding technical documents, radiance values for particular bands can be calculated. In such a way the training sample library will contain several examples of different stages of disturbance along tree species composition gradients and ground layer vegetation reflectance influence.

During the beaver surveys, the habitats are usually discovered after the beavers have established themselves and the flooding of surrounding is already extended over larger area. This discovery happens often several years after the beavers first built the dam. The first Sentinel-2 was launched in 2015; hence it was not possible to go back in the time series to look at the early stages of beaver-caused flooding with this satellite. Other alternative data source could have been using of Landsat-8 OLI but due to coarser spatial resolution we opted for Sentinel-2 data. Also, beaver sites smaller than 0.1 hectares and long but narrow ditches were not studied in this research due to their poor distinctiveness from the surrounding areas as determined using visual interpretation with aerial photographs.

Conclusions

In the summer months, when the vegetation is growing, the average forest reflectance values for the areas affected by beavers are lower in the visible and SWIR parts of the spectrum than in the non-affected areas. The NIR part of the spectrum shows some differences between the healthy and disturbed areas, but they are not as pronounced. In autumn, when trees shed their leaves and the grass starts to wither, the difference in the visible parts of the spectrum disappear, but the Sentinel-2 MSI bands representing the NIR parts of reflectance show smaller reflectance for the areas affected by beavers. In early spring, after snow has melted but the trees have not yet grown their leaves, the difference in the visible parts of the spectrum has not still manifested itself but the difference in the NIR reflectance remains. Multispectral vegetation indices, like NDVI, have significantly different values in the areas affected by beavers and in the non-affected areas across all phenological stages of the vegetation period. These differences are present in both evergreen and deciduous forests.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

These data were derived from the following resources available in the public domain: [Copernicus at https://scihub.copernicus.eu].

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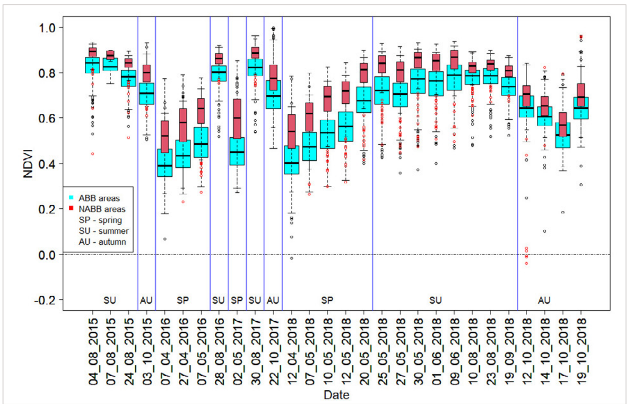
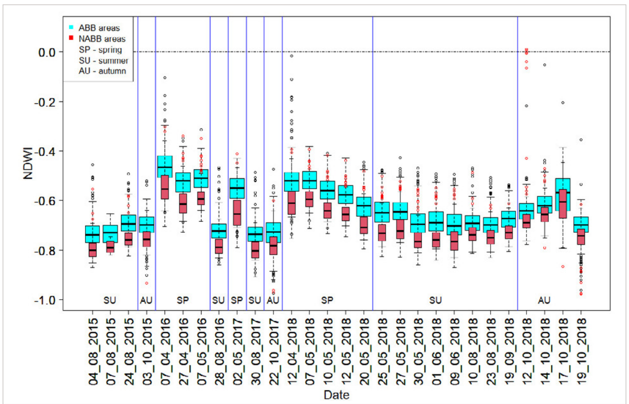
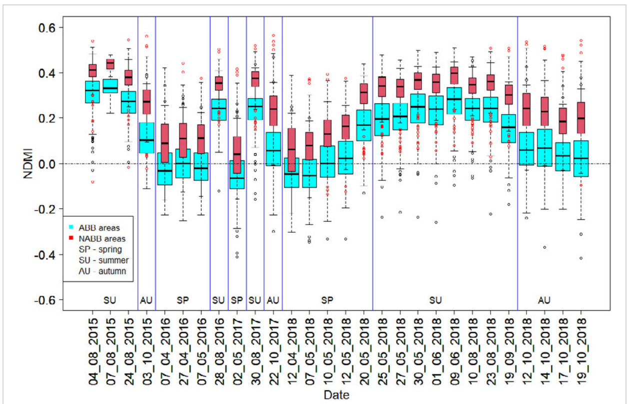
Appendix A. The boxplots of average index values over general forests in the ABB (affected by beavers) and NABB (non-affected by beavers) areas for all examined Sentinel-2 MSI images taken at different phenological stages



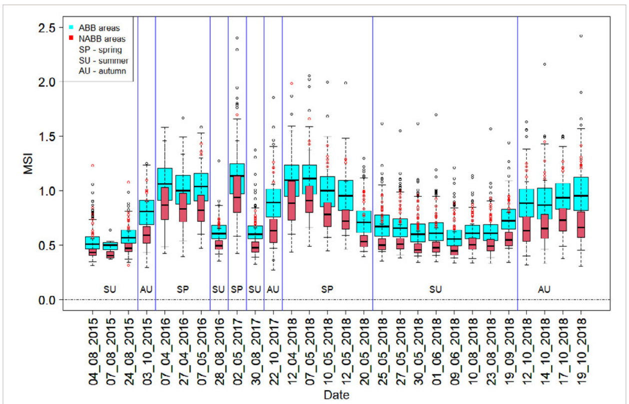
A1. The boxplot of average NDVI (Normalized Difference Vegetation Index) values over all samples in the ABB (affected by beavers) and NABB (no-affected by beavers) areas for all Sentinel-2 MSI images taken at different phenological stages



A2. The boxplot of average NDWI (Normalized Difference Water Index) values over all samples in the ABB (affected by beavers) and NABB (non-affected by beavers) areas for all examined Sentinel-2 MSI images taken at different phenological stages



A3. The boxplot of average NDMI (Normalized Difference Moisture Index) values over all samples in the ABB (affected by beavers) and NABB (non-affected by beavers) areas for all examined Sentinel-2 MSI images taken at different phenological stages



A4. The boxplot of average VMSI (Vegetation Moisture Stress Index) values over all samples in the ABB (affected by beavers) and NABB (non-affected by beavers) areas for all examined Sentinel-2 MSI images taken at different phenological stages