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RESEARCH PAPER

# Boreal to temperate forests transition within Kunashir Island (the Kuril Archipelago): Insights from the novel vegetation map

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## ABSTRACT

The vegetation of the Kuril Islands remains insufficiently explored due to their remote location and harsh environment. Understanding the factors that influence vegetation distribution in this extensive volcanic chain of islands, spanning over a thousand kilometers, is important for global biogeography. Our paper presents the first vegetation map of Kunashir Island from the Kuril archipelago, compiled using Sentinel-2 medium-resolution multispectral satellite imagery, incorporating original field research data and the Random Forest machine-learning algorithm. The temperate broad-leaved forests are mainly composed of *Acer mono* subsp. *mayrii* and *Quercus mongolica*, predominantly limited to the southwestern coast, and true-boreal dark-coniferous *Abies sachalinensis–Picea jezoensis* forests located in the northeast part of Kunashir. The vegetation distribution pattern is associated with the warming effect of the Soja current on the east coast of Kunashir Island and the cooling effect of the Kuril current on the west coast. Kunashir's vegetation displays features of an ecotone between temperate and boreal zones. Still, the boundary between these zones should be drawn within the island, rather than between Kunashir and Hokkaido or Kunashir and Iturup, as suggested in some previous biogeographic generalizations.

**Keywords:** multispectral satellite data, Sentinel-2, Random Forest, vegetation mapping, vegetation zonation, Kuril Islands

## РЕЗЮМЕ

**Корзников К.А., Альтман Я., Беляева Н.Г., Дзидзюрова В.Д., Кислов Д.Е., Линник Е.В., Петренко Т.Я., Крестов П.В. Переход от бореальных к умеренным лесам на острове Кунашир (Курильский архипелаг): Данные новой карты растительности.** Растительность островов Курильского архипелага остается малоизученным ввиду удаленности региона, сложных природно-климатических условий и неразвитой инфраструктуры. Понимание факторов, определяющих закономерности распределения растительного покрова в пределах этой более чем тысячекилометровой вулканической островной дуги, крайне интересны с точки зрения глобальной биогеографии. В настоящей статье приведена информация о новом картографическом продукте, отражающем актуальный растительный покров Кунашира, самого южного из островов архипелага. Классификация пикселей мультиспектральных спутниковых снимков Sentinel-2 выполнена при помощи алгоритма Random Forest на основе оригинальных данных полевых исследований. Выделено 12 единиц растительности с минимальной площадью полигона 0.1 га. Выявлена пространственная неравномерность распределения на острове широколиственных (*Acer mono* subsp. *mayrii–Quercus mongolica*) лесов умеренной зоны, приуроченных к юго-западному побережью острова и бореальных елово-пихтовых (*Abies sachalinensis–Picea jezoensis*) лесов, характерных для северо-восточной части острова. Такое распределение лесной растительности связано с отепляющим эффектом течения Соя на восточном охотоморском побережье острова и охлаждающим эффектом Курильского течения на западном океаническом побережье. Границу между растительными зонами следует проводить внутри Кунашира, а не между островами Кунашир и Хоккайдо, или между Кунаширом и следующим к северу островом Итуруп, как это предложено в ряде существующих биогеографических обобщений.

**Ключевые слова:** мультиспектральные спутниковые данные, Sentinel-2, случайный лес, картографирование растительности, зонирование растительности, Курильские острова

Kunashir is the southernmost island in the Kuril Islands, bordered by the Sea of Okhotsk and the Pacific Ocean, with a total area of 1 490 km$^2$ (Fig. 1a). The geological history of the island formed a landscape heterogeneity featuring mountainous volcanic areas. The highest elevation point on the island is the summit of Tyatya volcano, which stands at 1819 m above sea level, while the altitude of the Holocene isthmuses at former sea lagoon sites does not exceed 2–5 m a.s.l. The geological foundation of the island consists of volcanic rocks from the Neogene and Quaternary periods, including andesite and basalt lavas, tuffs, and tephra. Holocene deposits include both volcanic substrates and marine, river, and lake alluvium. The island hosts four active volcanoes, with the most recent eruption of the Tyatya volcano occurring in 1973. Post-volcanic phenomena, such as hot springs and hot solfatara fields, are common within the volcanic landscapes.

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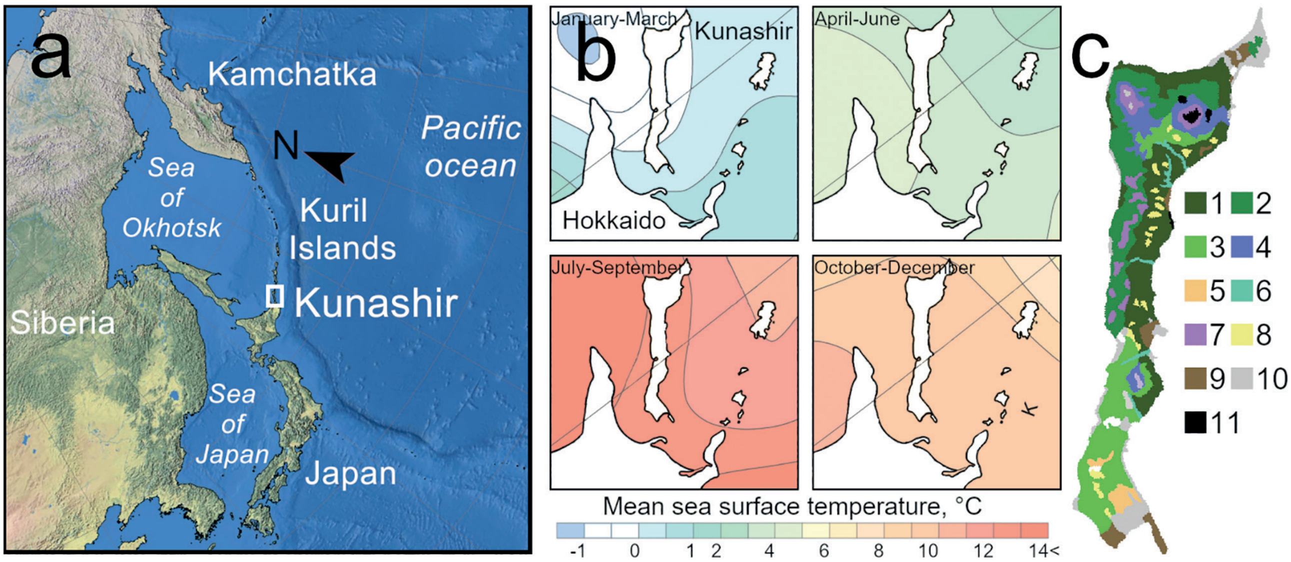



**Figure 1** Geographical position of Kunashir Island (a); variation of water surface temperature along the coastline of Kunashir Island (b); vegetation patterns showed on a previous-generation vegetation map (c) (redrawn after Grishin 2009): 1 – *Abies sachalinensis–Picea jezoensis* mountain forests with stands of *Picea glehnii* in wet and volcanic habitats; 2 – *Abies sachalinensis–Picea jezoensis* with mountain forests mixed with *Betula ermanii* and understory layer composed by *Sasa* spp.; 3 – *Abies sachalinensis–Picea jezoensis* mountain forests mixed with *Acer mono* subsp. *mayrii*, *Magnolia obovata*, *Kalopanax septemlobus*, *Phellodendron amurense*, *Quercus mongolica*, and woody lianas (*Actinidia kolomikta*, *Hydrangea petiolaris*, *Toxicodendron orientale*); 4 – *Betula ermanii* mountain and subalpine forests; 5 – *Acer mono* subsp. *mayrii–Betula ermanii–Quercus mongolica* forests with an admixture of other broadleaf species; 6 – Riparian forests composed of *Alnus hirsuta*, *Salix* spp., and *Ulmus* spp.; 7 – *Pinus pumila* thickets with an admixture of *Alnus alnobetula* s.l.; 8 – *Sasa* spp. thickets; 9 – wetlands, 10 – other non-forest vegetation; 11 – young volcanic deposits and volcanic rocks without the dense vegetation cover

The average annual temperature at sea level is +5.6°C, and the average annual precipitation is 1 474 mm, with 80 % of it falling as rain. Kunashir is prone to tropical cyclones (also known as typhoons) in summer and autumn, which bring heavy rainfall and strong winds. The climate of the island is significantly influenced by the surrounding water masses (Barkalov 2009). The island's western coast is warmed by the Soya current, an extension of the warm Tsushima current from the Sea of Japan (Takizawa 1982). In contrast, the east coast of the island is cooled by the waters of the Oyashio or Kuril current (Qiu 2001) (Fig. 1b).

Current knowledge of the vegetation of Kunashir Island primarily relies on a limited number of studies (Vasiliev 1946, Tatewaki 1958, Vorobyev 1963, Rozenberg et al. 1970, Barkalov 2002, 2009). A few studies have focused on specific forest types, including oak forests (Popov 1963), elm forests (Vasiliev 1979), and forests formed by *Picea glehnii* (F. Schmidt) Mast. (Sakhalin or Glen's spruce) (Shafranovskiy 1989, Krestov et al. 2003). A comprehensive view of Kunashir's vegetation was not done until the publication of the first vegetation map in the Atlas of the Kuril Islands (Grishin 2009). However, the manually created map at a 1:500 000 scale, does not accurately depict the precise boundaries between vegetation complexes but serves as a preliminary sketch rather than a complete representation of the island's actual vegetation (Fig. 1c).

In this paper, we present the map of the actual vegetation cover of Kunashir Island (Fig. 2). Our map is based on a combination of original field studies and medium-resolution multispectral images obtained from the Sentinel-2 satellite system. Additionally, we describe the various vegetation units on the map and explain their distribution patterns within the island and into the broader concept of vegetation zonation in the region.

## MATERIALS AND METHODS

To differentiate various vegetation types, referred to as "vegetation units", we used cloud-free multispectral Sentinel-2 Level2A images with a 20-meter resolution. Images were captured at different vegetation phenological stages, specifically on 6th May 2021, 10th June 2021, 18th July 2021, 27th September 2019, and 18th October 2019.

For the pixel-wise Random Forest (RF) classification, we included all spectral bands (B02-B8A, B11, and B12) and computed the values of three spectral indices: the normalized difference vegetation index (NDVI), normalized difference water index (NDWI), and bare soil index (BSI) (GitHub… 2023) from all satellite images. The optimal set of variables was determined by RF, analyzing their occurrence scores using the training data. We utilized the standard configuration parameters for RF from the Scikit-learn package (Scikit-learn... 2023) in Python for initialization, training, and validation stages.

To assess the RF model's performance, we employed the K-Fold cross-validation procedure and generated a confusion matrix for the test dataset. Specifically, we selected 100 trees for the random forest and performed K-fold validation with 5 folds using the cross_val_score function. The test dataset was created by randomly dividing the initial dataset into an 80 % training set and a 20 % test set.

We constructed the training set using data gathered from field observations during two expeditions in 2019 and 2021. This training set comprised more than 8 000 pixels, representing 12 vegetation units and surfaces of water bodies. The classification process occurred in four consecutive steps. During each step, RF selected the spectral data most suitable for distinguishing the vegetation units (Table 1). In the final

**Table 1.** Classification steps by the Random Forest analysis

| **Step #1** (contrast patterns) | **Step #2** (evergreen conifers) | **Step #3** (broadleaved forests) | **Step #4** (birch and riparian forests) |
|---|---|---|---|
| Dead forests | | | |
| Dwarf bamboo thickets | | | |
| Swamp woodlands | | | |
| Other non-forest vegetation | | | |
| Water bodies | | | |
| Wetlands | | | |
| | Dark coniferous | | |
| | Dwarf pine | | |
| | | Mixedwood | |
| | | Temperate oak | |
| | | Temperate broad-leaved | |
| | | | Birch |
| | | | Riparian |

stage, we merged stand-alone or small groups of pixels (less than 5) from any vegetation units with larger neighboring pixel groups, following a process of "map generalization" The presented version of the map underwent manual verification using an expert-based approach. We utilized very high-resolution optical images from various sources provided by the Google Earth program.

## RESULT AND DISCUSSION

### Vegetation units

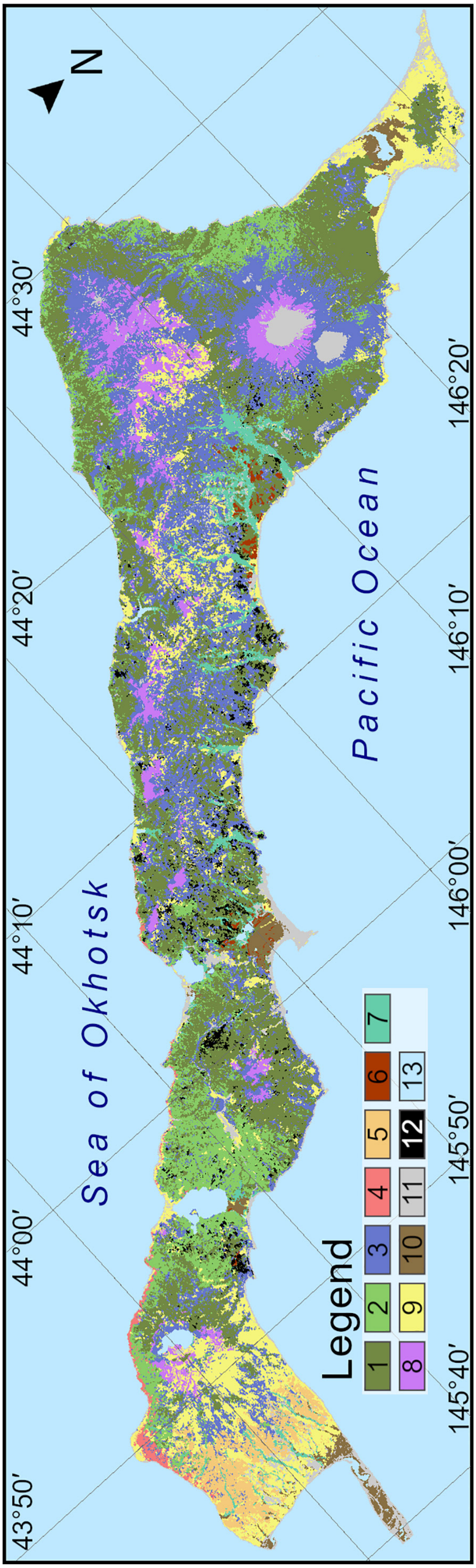
Forest vegetation covers more than 80 % of the Kunashir's area. Dark coniferous forests account for 29.4 % of the total area, while birch forests cover 25.4 %. Non-forest vegetation, primarily composed of *Sasa* spp. thickets occupy about 13.2 % of the area (Table 2).

Dark coniferous forests (a dark green color on the map, #1) include two types of evergreen stands. The first type represents the zonal vegetation and is characterized by the dominant tree species *Abies sachalinensis* (F. Schmidt) Mast. and *Picea jezoensis* (Siebold & Zucc.) Carrière. Occasionally, *Betula ermanii* Cham. and *Sorbus commixta* Hedl. are also found. The understory features *Sasa* spp. or typical boreal shrubs like *Rhododendron pentandrum* (Maxim.) Craven and *Vaccinium ovalifolium* Sm. with ferns (*Dryopteris expansa* (C. Presl) Fraser-Jenk. & Jermy, *Phegopteris connectilis* (Michx.) Watt) and mosses (*Dicranum* spp., *Hylocomium splendens* (Hedw.) Schimp., *Pleurozium schreberi* (Brid.) Mitt.). The second type of dark coniferous forest consists of monodominant stands of *Picea glehnii*. These forest stands are primarily located on marginal volcanic substrates on the slopes of the Mendeleev volcano. The undergrowth in these forests is characterized by dense thickets of *Sasa* spp. Additionally, significant areas of *Picea glehnii* artificial stands can be observed near the Golovnina volcano.

Mixedwood forests (a light-green color on the map, #2) are characterized by areas of forest cover where there is no clear dominance of either broad-leaved or coniferous tree species. This vegetation unit includes typical boreal forests where *Betula ermanii* coexists with *Abies sachalinensis* and *Picea jezoensis*. It also encompasses species-rich temperate forests where spruce and fir are accompanied by *Kalopanax septemlobus* (Thunb.) Koidz., *Magnolia obovata* Thunb., *Phellodendron amurense* var. *sachalinense* F.Schmidt, *Taxus cuspidata* Siebold & Zucc., *Quercus mongolica* Fisch. ex Ledeb. (incl. *Q. mongolica* var. *crispula* (Blume) H. Ohashi), and *Ulmus davidiana* var. *japonica* (Rehder) Nakai. Mixed boreal forests are primarily located in the northern part of the island and along the east coast, while mixed temperate forests are mainly found along the west coast and are primarily localized in the southern part of Kunashir. Despite efforts to distinguish and separate these two types of communities using multispectral reflectance, a suitable solution was not found. Therefore, they are represented as a single unit on the map. Further detailed ground-based studies, especially in the northern part of the island, specifically on the slopes of the Rurui volcano and the northern face of the Tyatya volcano, are required to refine the distribution of different community types within this unit.

Birch forests (a blue color on the map, #3) consist of primary communities found on mountain slopes, where *Betula ermanii* is the dominant species, and secondary stands at lower elevations, where *Betula platyphylla* Sukaczev coexists with *B. ermanii*. The upper limit of the forest in the mountains is marked by birch woodlands, often referred to as "krummholz". All birch forests feature an undergrowth of *Sasa* spp., but subalpine forests additionally include undergrowth of *Pinus pumila* (Pall.) Regel and *Alnus alnobetula* (Ehrh.) K. Koch. Areas of birch forests with forbs and herbs are relatively rare and are typically confined to damp terrains, such as river floodplains or the valleys of small watercourses in mountainous areas. In general, birch forests become more prevalent as one moves northward across the Kuril Islands, transitioning into a typical zonal vegetation type starting from the northern part of Iturup Island and occupying extensive areas in Kamchatka.

Temperate broad-leaved mixed forests (a coral color on the map, #4) are primarily concentrated in the southern half along the west coast, with no occurrence in the interior areas. These forests are characterized by a diverse range of tree species, including *Acer mono* subsp. *mayrii*, *Cornus controversa* Hemsl., *Kalopanax septemlobus*, *Magnolia obovata*, *Phellodendron amurense* var. *sachalinense*, *Prunus sargentii* Rehder,




*Prunus ssiori* F. Schmidt, *Quercus dentata* Thunb., *Q. mongolica*, and *Ulmus davidiana* var. *japonica*. Coniferous trees are exceptionally rare. The tree crowns often intertwine with woody lianas. Common liana species found in these forests include *Actinidia arguta* (Siebold & Zucc.) Planch. ex Miq., *Celastrus orbiculatus* Thunb., *Hydrangea hydrangeoides* (Siebold & Zucc.) Bernd Schulz, *Hydrangea petiolaris* Siebold & Zucc., and *Vitis coignetiae* Pulliat ex Planch. The understory layer is predominantly composed of *Sasa* spp., while tall herbs such as *Filipendula camtschatica* (Pall.) Maxim., *Laportea bulbifera* (Siebold & Zucc.) Wedd., *Parasenecio hastatus* (L.) H. Koyama, and others, along with a few fern species (*Deparia pterorachis* (Christ) M. Kato, *D. pycnosora* (Christ) M. Kato, *Dryopteris crassirhizoma* Nakai), growth in areas with moist and fertile soils. These sites are often associated with groundwater outlets, local depressions in the relief, and stream banks.

Temperate oak forests (an orange color on the map, #5) are primarily located in the gently sloping plain situated to the south of the Golovnina volcano caldera. The forests mainly comprise of trees that regrown after logging activities, effectively replacing the previously existing broadleaved or mixed stands. This type of forest is also known as coppice forest. The dominant tree species is *Quercus mongolica* with a minor presence of *Betula platyphylla* and *Populus tremula* L. The undergrowth is characterized by dense thickets of *Sasa* spp.

Swampy woodlands with stands of *Picea glehnii* (a dark red color on the map, #6) are situated along the eastern coast of Kunashir Island. These forested swamps are commonly found in poorly drained areas with limited water drainage. The undergrowth in these woodlands typically consists of marsh sedges and various species of *Sphagnum* mosses. In areas with higher moisture levels or along the edges of swamps, *Alnus hirsuta* may also be present.

Riparian broad-leaved forests (a sea-green color on a map, #7) encompass various types of trees stands. Those found in river floodplains are characterized by the presence of *Alnus hirsuta* (Spach) Rupr. and *Salix udensis* Trautv. & C.A. Mey. *Alnus hirsuta* also forms monodominant stands along lakeshores, swamp edges, and near groundwater outlets. Forests dominated by *Salix cardiophylla* Trautv. & C.A. Mey. are limited to the floodplains of the island's largest rivers on the northeast coast. *S. cardiophylla* forests grow on pebble substrates, while *Alnus hirsuta*–*Salix udensis* forests occur on sandy or muddy alluvial deposits. Shrubs are generally absent in the undergrowth of these forests, but a well-developed layer of tall grasses is common, often reaching heights of up to 2 m or more. Additionally, forest stands dominated by *Alnus japonica* (Thunb.) Steud. are distributed in the southern region of the island, specifically along streambanks of several watercourses originating from the southern slopes of the Golovnina volcano caldera (see the first record in Korznikov et al. 2021).

Dwarf pine (*Pinus pumila*) thickets (purple color on the map, #8) are sometimes accompanied by individual shrubs of *Alnus alnobetula* s.l. These communities are typically found in the upper parts of slopes and mountain peaks, including active volcanoes, primarily in the northern part of the island. *Pinus pumila* demon-

**Figure 2** Vegetation map of Kunashir Island. Vegetation units in the legend: 1 – dark coniferous forests; 2 – mixedwood forests; 3 – birch forests; 4 – temperate broad-leaved mixed forests; 5 – temperate oak forests; 6 – swamp coniferous woodlands; 7 – riparian broad-leaved forests; 8 – dwarf pine thickets; 9 – dwarf bamboo thickets; 10 – wetlands; 11 – other non-forest vegetation; 12 – dead forests; 13 – water bodies

**Table 2.** Explanation of the vegetation units

| Vegetation unit | Canopy dominants | Phytosociological class | Short description |
|---|---|---|---|
| Dark coniferous forests | *Abies sachalinensis*, *Picea jezoensis* | Vaccinio–Piceetea | Zonal forests, different successional stages |
| | *Picea glehnii* | | Edaphic climax on marginal substrates, different successional stages |
| Mixedwood forests | *Abies sachalinensis*, *Betula ermanii*, *Picea jezoensis* | Vaccinio–Piceetea | Primary mountain forests and secondary forests in low elevations |
| | *Abies sachalinensis*, *Acer mono* subsp. *mayrii*, *Quercus mongolica* | Transition between Vaccinio–Piceetea and Fagetea crenatae | Zonal forests, different successional stages |
| Birch forests | *Betula ermanii* | Ranunculo–Betuletea | Primary mountain forests and secondary forests in low elevations |
| | *Betula platyphylla* | Unknown | Secondary forests |
| Temperate broad-leaved forests | *Acer mono* subsp. *mayrii*, *Quercus mongolica*, *Ulmus japonica* | Fagetea crenatae | Enclaves of temperate forests, different successional stages |
| Temperate oak forests | *Quercus mongolica* | Fagetea crenatae | Secondary forests from the southernmost part of the island |
| Swamp woodlands | *Picea glehnii* | Vaccinio–Piceetea | Azonal forests at plains along the east coast of the island |
| Riparian | *Alnus hirsuta*, *Salix udensis* | Salicetea sachalinensis | Riparian forests |
| | *Salix cardiophyyla* | | Riparian forests from the east coast of the island |
| | *Alnus japonica* | Alnetea japonica | Riparian forests from the southernmost part of the island |
| Dwarf pine thickets | *Pinus pumila* | Vaccinio–Piceetea | Primary communities from the upper vegetation belt and an edaphic climax in the areas of active volcanism |
| Dwarf bamboo thickets | *Sasa* spp. | Unknown | Secondary communities replaced forests |
| Wetlands | Graminoids and mosses | Phragmito–Magnocaricetea, Scheuchzerio–Caricetea | Riparian zones along freshwater bodies |
| Other | Various | Various | Tall-herbs thickets, anthropogenic meadows, sandy and gravel beaches, primary communities on bedrocks, volcanic tephra, and other |

**Full names of vegetation classes from the table:** Alnetea japonicae Miyawaki, Fujiwara et Mochizuki 1977; Fagetea crenatae Miyawaki, Ohba et Murase 1964; Phragmito–Magnocaricetea Klika in Klika et Novák 1941; Salicetea sachalinensis Ohba 1973; Ranunculo japonici–Betuletea ermanii Ohba ex Ohba 1973 nom. inver.; Scheuchzerio palustris–Caricetea fuscae Tx. 1937; Vaccinio–Piceetea Br.-Bl. in Br.-Bl. et al. 1939.

strates high ecological plasticity, allowing it to form thickets in harsh environment sites, such as young volcanic deposits and fumarole fields.

Widespread throughout Kunashir Island are thickets of dwarf bamboo *Sasa* spp. (yellow color on the map, #9), which indicates past disturbances in the natural forest cover. Dwarf bamboo rapidly colonizes disturbed forest areas and inhibits the regeneration of woody species, leading to a delay in succession for many years (Altman et al. 2016). Within the dense bamboo thickets, one can often find scattered individual trees or shrubs, such as *Abies sachalinensis*, *Betula ermanii*, *B. platyphylla*, *Pinus pumila*, and *Quercus mongolica*. Spaced tens, or hundreds of meters apart, what make an impression of a park landscape.

Diverse wetlands (brown color on the map, #10) are primarily situated along the edges of freshwater reservoirs, which were previously lagoons that became isolated from the seas during the Holocene. Wetland vegetation in these areas exhibits high plant diversity and is characterized by the presence of various species from the Cyperaceae family, particularly *Carex* spp. Additionally, common species found in these wetlands include *Phragmites australis* (Cav.) Trin. ex Steud. and *P. japonicus* Steud. and hydrophilic mosses, such as *Sphagnum* spp.

The unit of "other non-forest vegetation" (grey color on the map, #11) encompasses a variety of non-forest communities on Kunashir Island. These communities include herbaceous plants found on pebbles and sands along seacoasts, groups of pioneer plants on eroded slopes, volcanic landscapes, including fresh volcanic deposits, meadows (incl., arable lands), semi-alpine tundra communities, urban and roadside vegetation.

## Forest disturbance recognition

During the extratropical cyclone event in December 2014 and two typhoons in the autumn of 2015, Kunashir's forests experienced extensive windthrow disturbances. These events created favorable conditions for bark beetle outbreaks, particularly *Ips typographus japonicus* Niisima, 1909, exacerbating the decline of forested areas and affecting hundreds of hectares of forest cover. Both *Picea jezoensis* and *P. glehnii* forests were impacted by bark beetles significantly in the central part of the island (Kislov et al. 2021).

According to the results of RF, approximately 1.8 % of the island's area consists of dead forest stands (black color on the map). The methodology used for vegetation mapping did not allow for the separate identification of areas affected by storms versus those impacted by bark beetle outbreaks. Additionally, the spatial resolution of the data used limited the ability to conduct a detailed assessment of the extent of the disturbances. As a result, the presented map only displays the largest patches of disturbed forests without identification of the disturbance type.

Previously using convolutional neural network algorithms and high-resolution satellite imagery, we estimated that more 2 173 hectares (or about 1.82 % of the island's area) were affected by massive windthrows (Kislov & Korznikov 2020, Kislov et al. 2021).

## Future perspectives

Vegetation maps, even when constructed using satellite data, represent an interpretation of the vegetation cover rather than an exact replication of the actual vegetation on the ground. Our map relies on remote sensing data, which provides information about the spectral characteristics of the vegetation. However, the map may not capture all the subtleties and complexities of the vegetation diversity. Therefore, while a satellite-based vegetation map offers valuable insights into the distribution and composition of vegetation, it should be regarded as a representation or approximation of the actual vegetation rather than a flawless model of it.

Further subdivision of mixed forests is necessary in future editions of the vegetation map. Specifically, they should be categorized into boreal forests, consisting of conifers and *Betula ermanii*, and temperate forests, comprising conifers and temperate broadleaf species. This subdivision will offer a more detailed and accurate representation of the various vegetation types present on Kunashir Island.

The challenges in distinguishing plant communities with similar spectral reflectances, such as the *Abies sachalinensis–Picea jezoensis* and *Picea glehnii* forest stands which we stitched to the one unit "dark coniferous forests", underscore the limitations of relying solely on middle-resolution multispectral images for vegetation mapping. To overcome this limitation and enhance mapping accuracy, the adoption of very high-resolution satellite data can be advantageous. These images offer more detailed information on the vegetation shape and structure and enable better recognition of vegetation (Flood et al. 2019, Kattenborn et al. 2019).

In addition to using advanced satellite data, field studies in remote and inaccessible areas is necessary. These studies provide ground-truthing and validation for satellite imagery, thus improving the accuracy of vegetation mapping.

## The problem of vegetation zonation

The position of the vegetation of Kunashir Island within the broader vegetation zone system has some ambiguity. The zonal vegetation on the island primarily consists of spruce-fir forests, classified as the vegetation class Vaccinio-Piceetea Br.-Bl. in Br.-Bl. et al. 1939 within the boreal zone (Miywaki 1979). Several large-scale vegetation maps, including those in the "Vegetation of the USSR" series (e.g., Belov et al. 1986), have labeled Kunashir Island's vegetation as taiga or boreal forests. However, the presence of extensive broad-leaved forests on the island suggests the possibility of considering Kunashir's vegetation as a distinct hemiboreal zone (Hamet-Ahti et al. 1974), or as a "coniferous-broad-leaved forest zone" (Kolesnikov 1963), or as an ecotone between the temperate and boreal zones (the vegetation classes Fagetea crenatae Miyawaki, Ohba et Murase 1964 and Vaccinio-Piceetea) (Miyawaki 1984).

However, when delineating the boundaries of vegetation zones, it is not accurate to categorize the entire island's vegetation as an ecotone. The significant vegetation change occurs within Kunashir and cannot be overlooked when defining the borders of vegetation zones. The northeastern part of the island is characterized by boreal forests dominated by spruce and fir, even at low elevations above sea level. In contrast, the southeastern part of the island is dominated by temperate broad-leaved forests. These differences reflect the inequality of climatic conditions within the island. Therefore, the northeastern part of the island should be recognized as fully belonging to the boreal zone, while the vegetation of the central and especially the southern eastern part of the island represents the temperate or the hemiboreal zone, depending on the biogeographical context. The diversity of Kunashir's vegetation makes it an ideal system for studying the coexistence of different zonal types of vegetation and their responses to climate change. Our map can serve as a valuable starting point for tracking long-term changes in vegetation cover.

# CONCLUSIONS

Accurately mapping and classifying the vegetation cover on Kunashir Island were challenged in the past because of the limited infrastructure and rugged terrain accompanied by the dense almost impenetrable thickets of dwarf bamboo (Sasa spp.). The application of novel remote sensing multispectral data and machine learning techniques presented us with an opportunity to perform an identification of distinct vegetation units and vegetation mapping.

The next editions of the vegetation map could be developed using more sophisticated techniques, such as the utilization of very high-resolution satellite data for machine learning techniques based on neural network algorithms this will increase the number of classified vegetation units and spatial resolution.

A more accurate representation of the vegetation patches allows us to better understand the patterns between climatic and geomorphological conditions and vegetation cover. The map we have compiled is a good reference point for further changes in vegetation cover under the influence of factors of climatic, volcanic, or anthropogenic origin.

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