ORION: biOdiveRsity Impacts of shrub expansiON in the Chamonix valley

Final report

31/08/2023

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I. Introduction

Context and issues

While the upper limit of the forest has been studied and monitored for many years, **the distribution of low woody plants (or heaths) in the Alps is often poorly taken into account in the mapping and management of mountain environments**[1] . However, heaths of the Ericaceae family now represent a structuring and sometimes dominant habitat in mountain vegetation cover, and their expansion at the expense of grasslands can lead to a number of "ecosystem disservices". The replacement of grassland by heathland risks i) leading to a local decline in floristic diversity[2] , ii) altering the plant resources and habitat available to wild and domestic herbivores[3] and iii) changing the landscape from the point of view of tourists and hikers. In recent years in the Alps, there is suspicion of a sharp increase in heathland growth[4,5] , which is thought to have been encouraged both by global warming, which has reduced the duration of snow cover[6] , and by the abandonment of pastoralism in favour of tourism.

The Mont-Blanc massif is an emblematic site for the effects of climate change in the Alps[7] . In the same way as the melting of glaciers and permafrost in the high mountains, the erosion of biodiversity is a critical consequence of global warming that needs to be monitored from the point of view of territorial management and conservation. According to the INPN[8] , a third of the flora of high altitude open environments (grassland, moorland and snow combs) is considered to be under threat in the region, due to changes in habitats and global warming. **Heathland is a particularly dominant habitat in the Chamonix valley**, and since the 1970s, thanks to aerial photos, we have seen a significant expansion of low-growing ligneous plants in alpine environments (Figure 1). Mountain meadows have become increasingly rare and fragmented, isolated between forest, moorland and high mountain faces.

In order to preserve and manage high-altitude open environments and the associated biodiversity, **local managers have expressed their need for tools to monitor the spatial and temporal evolution of these habitats. There is a shared observation that satellite images are not being taken into account** in the definition of their biodiversity management strategy due to (i) a lack of detail in the products proposed to be operational (e.g. THEIA OSO map, Copernicus products; Figures 1, A1) and (ii) a lack of availability, synthesis in the form of indicators and access to tools produced by the scientific community.

The commissioning of new satellites such as Sentinel-2 offers scientists and land managers the opportunity to improve spatio-temporal monitoring of mountain environments[9] , thanks to the improved spectral, spatial and temporal resolution of this new generation of images. A recent study carried out by our team demonstrated the potential of Sentinel-2 to detect the accumulation of anthocyanin pigments during the autumn in heathlands dominated by Ericaceae[1] , making it possible to refine land-use maps by distinguishing between heathlands and grasslands. At the same time, we have set up a network of '**photo traps'** in the Chamonix valley, providing an effective tool to complement satellite images in observing the use of mountain habitats by wildlife[10] .

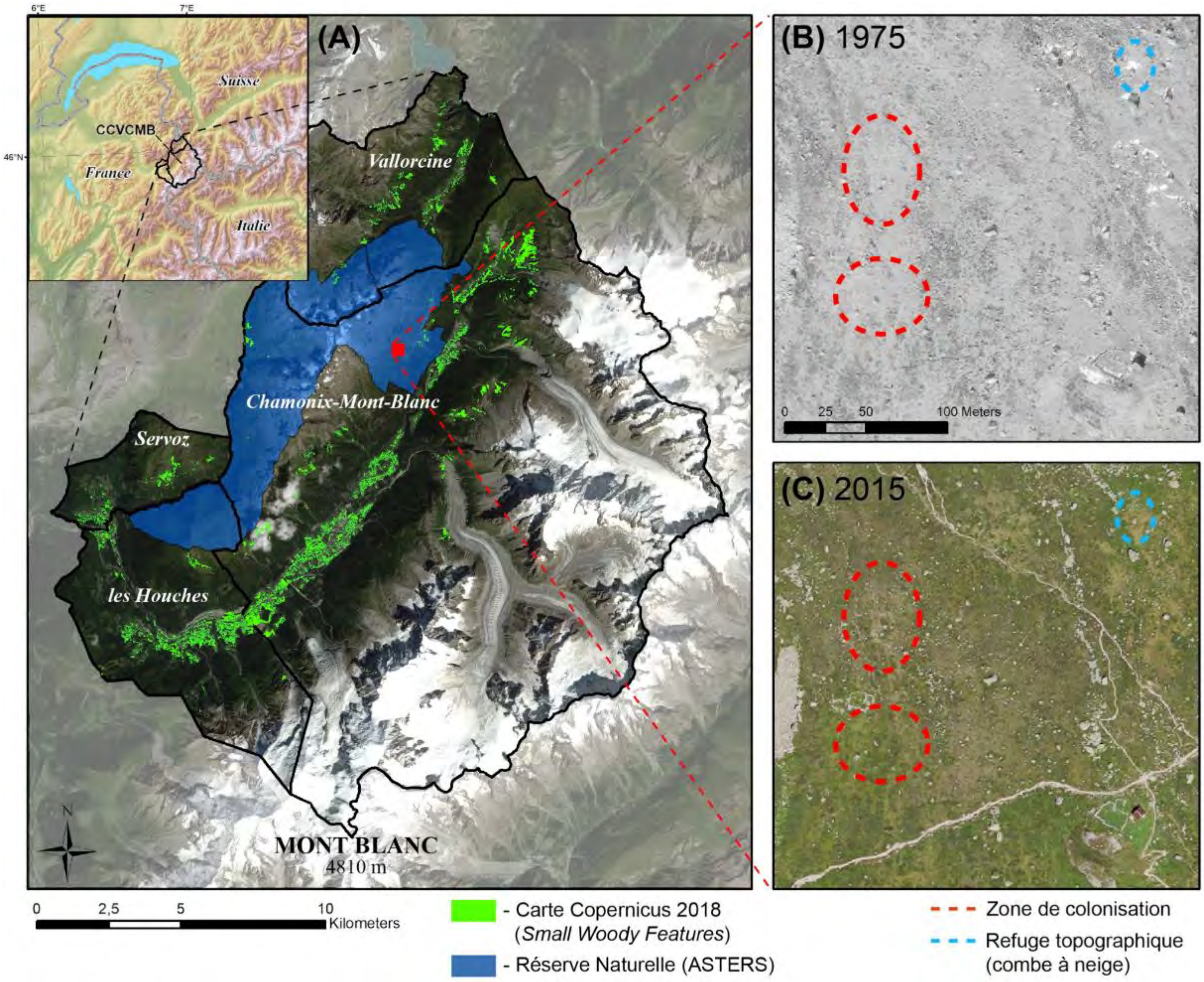


Figure 1 (**A**) Map of the study area centred on the Communauté de Communes de la Vallée de Chamonix Mont-Blanc (CCVCMB), showing the distribution of *Small Woody Features* proposed by Copernicus at European level. The proposed mapping does not correspond to the distribution of moorland and low woody species present in open supra-forest environments. Panels **(B)** and **(C)** show aerial photos of the Lac des Chéserys sector of the Aiguilles Rouges in Chamonix, taken in 1975 and 2015. The strong expansion of heathland at the expense of grassland is clearly visible (red ellipses and elsewhere), except in certain specific contexts such as a snow-comb hollow (blue ellipse).

Project objectives

The ORION project aims to capitalise on these recent methodological advances, with the aim of providing operational services to decision-makers to help them manage the expansion of heathland and, more generally, the dynamics of habitats (forest, heathland, grassland) in their areas. We are proposing a **multi-trophic approach** to understanding the consequences of grassland closure on floristic diversity and on the availability of habitat for wild and domestic fauna (grazing). We will provide decision-makers with spatially explicit tools that can be renewed and updated regularly over the coming years, thanks to the continuous availability of satellite images. In concrete terms, we plan to produce: (i) high-resolution mapping of the distribution of environments (forest, moorland, grassland, rock and bare ground) based on satellite images and validated by ground observations - **WP1**, (ii) indicators of floristic diversity and wildlife use based on moorland cover - **WP2**, and (iii) maps of high-stake areas where moorland dynamics are particularly important to monitor - **WP3**. All these tools, including interactive maps, will be integrated into the **Mont Blanc Atlas**, a web platform designed to share the results of scientific work carried out in the Mont Blanc massif with decision-makers and the general public - **WP4** (Figure 2).

To carry out this work, we have set up a partnership between the Centre de Recherches sur les Ecosystèmes d'Altitude **(CREA Mont-Blanc)**, a Chamonix-based NGO specialising in the link between scientific research in ecology and decision-makers, and the Laboratoire d'Ecologie Alpine **(LECA)**, a laboratory of Grenoble Alpes University and Savoie Mont Blanc University. Our work is aimed at technicians and decision-makers in the Communauté de Communes de la Vallée de Chamonix-Mont-Blanc (**CCVCMB**) and also managers of nature reserves in Haute-Savoie and the Chamonix valley (**Asters**). To bring this project to fruition, we have set up regular exchanges with our scientific partners and the managers and decision-makers involved in the project.

Figure 2. Diagram of the project's four *Work Packages.*

II. Methods

Habitat mapping

Calibration points

The first phase of the project involved defining a typology of habitat classes representative of the Chamonix valley and sufficiently distinct from a spectral point of view to be differentiated by the satellite. This process resulted in ten classes designed to cover the entire territory of the CCVCMB: **urbanised areas**, bodies of **water**, **mountain meadows**, **forest**, **forest edge** (tall trees and shrubs such as green alder, willows and scattered trees), **productive meadows or alpine pastures**, **Ericaceae heaths**, **alpine meadows** with lower productivity, areas of **rock or bare ground** and finally **areas of snow or ice** in the high mountains. Here is a more detailed description of some of the key habitat classes, particularly as regards vegetation:

- **Subalpine meadows**: meadows surrounded by moorland and/or forest, which are maintained by past, present or both domestic grazing (for example below the Loriaz refuge, towards the

Chalets de Chailloux, at the foot of the Combe de la Pendant) but already at altitude (above 1800 m) and not at the bottom of the valley.

- **Mountain meadows**: meadows maintained by human activity at the bottom of the valley, for example the fields or hay meadows at Le Tour or Servoz.
- **Forest boundary**: transition zones with high trees or shrubs (alder, willow) at low density. This is the upper limit of the trees and tall woody plants, and may be at the interface with bare ground, moorland or grassland.
- **Heath**: fairly dense areas of heathland characterised by the presence of shrubs from the Ericaceae family and locally dwarf juniper.
- **Heathland/grassland ecotone** = areas with a mosaic of heathland and grassland, where the model predicts a high probability of the presence of both heathland and grassland.
- **Alpine meadow**: a high-altitude meadow whose presence is mainly due to climatic factors and not to pastoral practices (e.g. around the Couvercle refuge).

Once the classes had been established, the next step was to define calibration points by photo-interpretation using the colour infra-red aerial image (IRC) taken in July 2020 and available on the IGN Géoportail. Table 2 in the Results section lists the number of training points established for each class.

Calculation of explanatory variables

Table 1 lists the explanatory variables selected, which were derived from the digital terrain model (DTM) and Sentinel 2A and 2B images over the period 2017 to 2021. Only variables with a correlation coefficient of less than 0.7 with the other variables considered were retained for the next modelling stage. **For the variables derived from Sentinel-2, we calculated each variable at annual level and then averaged them over the period 2017-2021 in order to** quantify the "typical" values for the study period and to smooth out inter-annual variability. Appendix S1 provides methodological details on the calculation of the annual maps of degrees of snow-free days (SF-GDD), which involved cross-referencing the maps of the duration of snow cover distributed by the THEIA Pole[11] for the French Alps with temperature data from Safran meteorological reanalyses supplied by Météo-France[12] . The spectral indices (NARI[1] , BI[13] , NDMI[14]) were calculated on the Google Earth Engine platform, using the formulae presented in Table 1. To estimate phenological parameters (SOSD and EOSV[15]), we downloaded products derived from Sentinel-2 images provided by the Copernicus services. Finally, the topographic parameters (TPI, DAH) were estimated from the 25m DTM available for Europe. The TPI (Topographic Position Index) quantifies the convexity and concavity of the terrain, which is known to have significant effects on alpine vegetation. The DAH (Diurnal Anisotropic Heating index[16]) quantifies the exposure of slopes to sunlight, for example, between a north and south slope. All these explanatory variables were compiled in the form of a raster stack covering the CCVCMB area at 10m spatial resolution.

Variable	Nom complet	Source	Méthode	Portail des données
SF-GDD	*Snow-free growing degree days* Somme des degrés jours sans neige	Produit neige CESBIO ; données de T° du modèle Safran de Météo-France	Annexe S1	https://theia.cnes.fr/
NARI	*Normalized Anthocyanin Reflectance Index* Indice normalisé d'anthocyanines	Images Sentinel 2A-B	((1/B3) - (1/B5)) / ((1/B3) + (1/B5)) *image automnale*	Google Earth Engine
BI	*Brightness Index* Indice de luminosité	Images Sentinel 2A-B	sqrt(((B4*B4) / (B3*B3))/2) *image automnale*	Google Earth Engine
NDMI	*Normalized Difference Moisture Index* Indice normalisé d'humidité	Images Sentinel 2A-B	(B8 - B11) / (B8 + B11) *image estivale*	Google Earth Engine
SOSD	*Start of Season Date* Date de début de saison	Copernicus vegetation parameters	fourni	https://land.copernicus.eu/
EOSV	*End of Season Value* Valeur de prod. de fin de saison	Copernicus vegetation parameters	fourni	https://land.copernicus.eu/
TPI	*Topographic Position Index* Indice de position topographique	Copernicus EU-DEM	calculé dans R avec le package 'raster'	https://land.copernicus.eu/
DAH	*Diurnal Anisotropic Heating index*	Copernicus EU-DEM	calculé dans SAGA GIS	https://land.copernicus.eu/

Table 1. The list of explanatory variables selected to predict the different habitat classes, citing the source of each variable and specifying whether it was calculated by ourselves or by the data providers. When we calculated the index from Sentinel-2 images, the formula is indicated in the Method column (for example, B3 corresponds to the green channel of the image, B4 to the red channel, etc.). For all variables except TPI and DAH, we calculated the index for the years 2017 to 2021 and then calculated the average value for each pixel. The topographical variables (TPI and DAH) remained fixed during the prediction period. Details of the calculation of the sum of snow-free days variable (SF-GDD) are provided in Appendix S1.

Calibration of the predictive model

We calibrated a ***random forest*** algorithm based on a table grouping the training points with the different explanatory variables listed in Table 1. To do this, we used the 'train' function in the 'caret' package in R software version 4.2.1. We partitioned the data into a training (⅔) and evaluation (⅓) dataset by calibrating a random forest model each time. We repeated this procedure 1000 times to assess the quality of the classification. For the final model, we calibrated a random forest on all the training points (N = 883). Finally, we applied the model to the entire study area from the stack of explanatory variables using the 'predict.train' function to generate the predicted habitat map.

The heathland-grassland ecotone class was assigned at a second stage, after calibration of the random forest model. In the field, **it is often possible to observe heathland intermingled with grassland in the form of a mosaic**, which makes it difficult to distinguish clearly between these two habitats in certain cases, particularly at a resolution of 10 m, which corresponds to the size of the Sentinel-2 pixels. This confusion was reflected in the model, which sometimes simultaneously predicted a high probability of heathland and grassland for the same pixel (Figure A2). To take account of this complexity, we added a class entitled heathland-grassland ecotone, which was assigned when the model predicted a probability greater than 0.3 for both the heathland class and the grassland class.

Summer 2022 field campaign

Between mid-July and the end of August 2022, the CREA Mont-Blanc team, reinforced by scientific collaborators and above all by a team of volunteers mobilised for the summer season, carried out **20 days of fieldwork** to measure vegetation and habitat (Figure 3). The protocol, which was designed to be compatible with that of the Alpages Sentinelles programme carried out as part of the Alps Workshop Zone, consisted of laying two metres 20 m long on the ground in the form of a cross, and then taking the following measurements every 50 cm: the height of the plant canopy, the type of soil (litter, vegetated, bare soil, gravel pebbles between 5 mm and 25 mm, pebbles between 25 mm and 25 cm, boulders > 25 cm, lichen, moss), as well as the heathland species that touched the metre held vertically, herbaceous graminoids, herbaceous forbs and trees and shrubs if they were less than 1m50. To make the surveys easier for people with no botanical training, we kept to the functional group level for forbs and graminoids without identifying the species. Visually, we also estimated the coverage of the different vegetation strata over the whole plot (less than 10 cm, between 10 and 40 cm, between 40 cm and 1m30, between 1m30 and 4 m, greater than 4 m, and the proportion of bare soil/rock).

In order to structure our field sampling and to limit spatial autocorrelation between measurement points, we generated a 250 x 250 m grid covering all the supra-forest environments of the CCVCMB. We then carried out our habitat surveys within as many of these grids as possible, as well as in front of each photo trap (Figure A3). In all, we carried out **142 vegetation measurement points**, with a total of **11,000 height and soil measurements** and the **recognition of 22,785 plants**.

Field validation of the habitat map

In order to assess the ecological relevance of the habitat map generated, we carried out several analyses that cross-referenced the final classification with the habitat surveys carried out in the field (Figure 3). The first involved extracting the habitat class for each survey point, and then quantifying the abundance of functional groups (heath, graminoid, forbs) for each map class concerned: heath, heathland-prairie ecotone and alpine meadow. The second analysis involved calculating the average canopy height for each survey, and then quantifying whether the different habitat classes on the map corresponded to systematic variations in vegetative height. Finally, we extracted the explanatory variables (Table 1) for each survey point in order to test the possibility of refining the classification, in particular by distinguishing *Rhododendron* heaths from low *Vaccinium* heaths. We carried out a PCA-type multivariate analysis to see whether some of the explanatory variables used to generate the habitat map could also be used to i) refine the classification and ii) predict certain functional properties of the habitats surveyed in the field, such as canopy height.

Figure 3. Photo of the field protocol in progress on the top of Peclerey mountain at 2450 m, overlooking the Argentière glacier. You can see the two 20 m metres laid out on the ground in the form of crosses, as well as the teamwork which consisted of two pairs on each transect: one person measuring and one person noting. Figure A3 shows the location of the 142 habitat surveys carried out in the Chamonix valley.

Floristic and faunistic diversity indicators linked to moorland cover

As part of the project's second Work Package, we were interested in the consequences of greater heathland cover on plant diversity and also on the use of habitats by certain targeted fauna species (mountain hare and chamois). In order to test our hypothesis that a higher cover of Ericaceae would lead to a decrease in floral diversity locally, we obtained phytosociological surveys carried out by the Conservatoire Botanique National Alpin (CBNA) in the Haute-Savoie region between 2011 and 2021. We then extracted the surveys located above 1700 m altitude and characterised by the presence of an Ericaceae heath species and/or dwarf juniper (*Juniperus communis nana), which* led to a selection of 144 surveys in the department. For each survey, we calculated the total floristic species richness as well as the percentage cover of shrub heath, *Rhododendron ferrugineum* and *Vaccinium uliginosum.*

We also looked at the link between moorland cover and habitat use by wildlife, in particular **the chamois** (*Rupicapra rupicapra*) and **the mountain hare** (*Lepus timidus*). The first step was to estimate the probability of these species occupying different habitats throughout the year. This index was calculated from the contacts recorded by the photo traps. For chamois, we also modelled the probability of occupation according to the height of the plant canopy, to check whether the species tends to avoid habitats with too high a canopy. For the hare, we extrapolated the results observed by photo trap concerning the frequentation of different habitats depending on the season, using the 10 m habitat map.

III. TECHNICAL RESULTS Technical results

Habitat mapping

The confusion matrix resulting from the random forest indicates an average error rate of 15%, although there is considerable variation between the different classes. Mountain meadows and subalpine alpine meadows show the highest error rates (25 and 34%, respectively). These two habitats are dependent on human activities and are highly fragmented within the landscape, making them particularly difficult to model. The error rate for the water class was also high (27%), which was partly due to confusion with the shadow zones in the high mountains under north-facing walls and water surfaces, as these two objects tend to absorb the majority of visible and infrared waves. For the heathland class, the error rate was 14%. Table A1 shows the importance, i.e. the predictive power, of each variable included in the final model: the most important variable was the SF-GDD, which quantifies the energy available to plants along the altitude gradient. The soil brightness variable (BI) calculated during the autumn season was also very effective in differentiating between different types of vegetation and land use. In the end, the topographical variables (TPI and DAH) had little predictive power.

	N	Forêt	Neige et glace	Lande	Prairie montagnarde	Prairie alpine	Rocher et sol nu	Prairie subalpine	Limite de la forêt	Eau	Urbain	Taux d'erreur (%)
Forêt	119	**112**	0	0	3	0	0	0	4	0	0	0,06
Neige et glace	27	0	**26**	0	0	0	1	0	0	0	0	0,04
Lande	209	0	0	**180**	0	16	0	2	11	0	0	0,14
Prairie montagnarde	36	7	0	0	**27**	0	0	0	1	0	1	0,25
Prairie alpine	116	0	0	24	0	**89**	2	1	0	0	0	0,23
Rocher et sol nu	111	2	0	0	0	1	**105**	0	0	0	3	0,05
Prairie subalpine	56	0	0	13	0	4	0	**37**	2	0	0	0,34
Limite de la forêt	105	8	0	10	0	0	0	0	**87**	0	0	0,17
Eau	15	0	0	0	1	0	2	0	0	**11**	1	0,27
Urbain	53	0	0	0	0	0	5	0	0	0	**48**	0,09
	∑ = 883											**$\bar{x}$ = 15%**

Table 2. The number of training points (*N* = 883) and the confusion matrix resulting from the *Random forest* model for each habitat class. The error rate is also given per class and at the global level (average error of 15%). The error rates for the heathland, alpine grassland and subalpine meadow classes are lower for the final map following the addition of the heathland-grassland ecotone class (which corresponds to pixels where the model predicts a high probability of both heathland and grassland).

The relationships between the different explanatory variables and the habitat classes are presented in Figure 4. **As for all the classes, for heathland the most important variable was SF-GDD, which captures the topo-climatic gradient** of snow cover and temperature variations, followed by **SOSD, NARI and BI**. Although this phenomenon remains a field of research[17] , it seems consistent that shrubs start their growing season earlier in spring than adjacent grasslands, which tend to remain under snow for longer (SOSD). NARI, which is sensitive to the accumulation of anthocyanin pigments in the leaves of Ericaceae[1] , has proved effective in helping to distinguish heathland from grassland. Finally, the explanatory power of BI is also logical given that grasslands tend to be lighter, whereas heathlands are characterised by darker canopies, particularly in autumn.

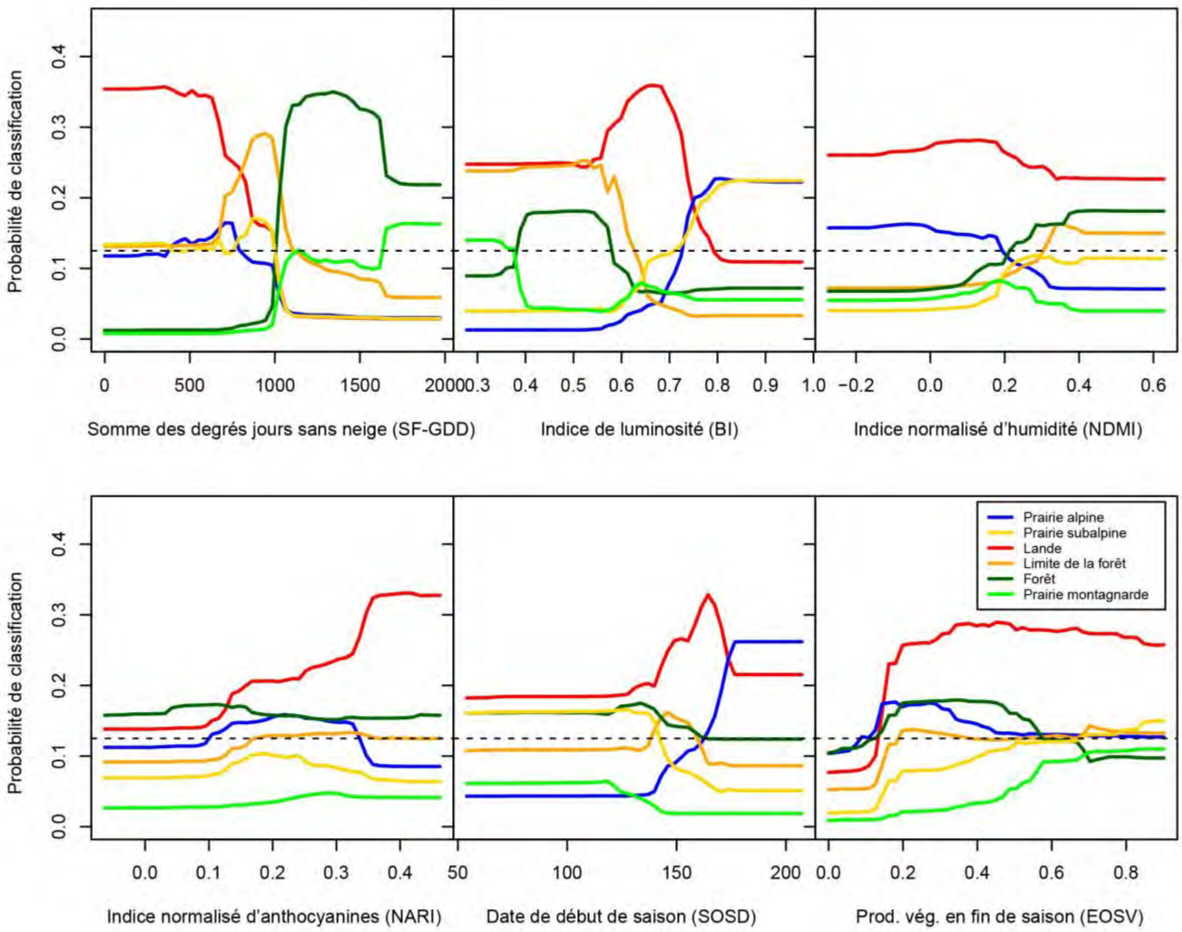


Figure 4: Response curves (*partial dependency plots*) for the classification probabilities of each habitat as a function of the explanatory variables. The higher the probability value for a given class, the greater the predictive power of the variable. For example, the probability of classification of the heathland class increases sharply when the NARI values exceed a threshold of 0.3.

The result is a habitat map of the CCVCMB at 10 m resolution (Figure 5A). **Figure 5B shows that the ORION map provides more information on alpine habitats than the maps available at French (OSO) and European (CORINE) level.** Generally speaking, in the CCVCMB, **moorland is the dominant habitat in the supra-forest environments throughout the valley, interspersed with a few alpine pasture areas** such as those at Chailloux, Pendant, Col de Balme and Loriaz. At higher altitudes, there are areas of alpine meadow, for example at Couvercle, at the top of the southern balcony of the Aiguilles Rouges, and at the top of the Bérard valley. Generally speaking, meadows (alpine meadows and alpine meadows) cover around 5% of the territory of the CCVCMB, and represent a fairly rare and fragmented environment, to be monitored from the point of view of conservation and management (Figure 6).

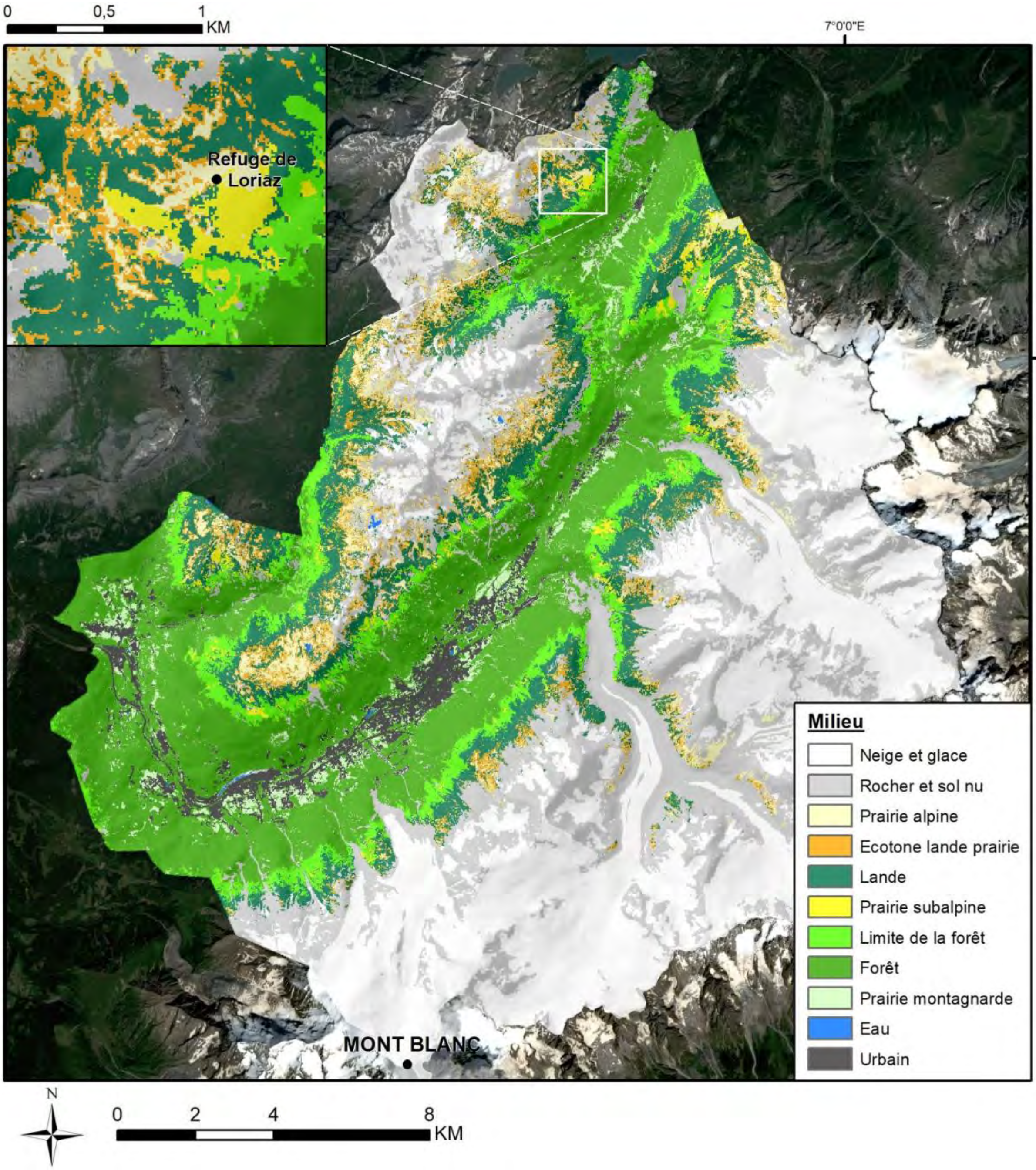


Figure 5A. Final habitat map at 10 m spatial resolution for the CCVCMB territory for the 11 classes modelled. The zoomed-in map at the top left shows the spatial variation of environments in the Loriaz mountain sector in the commune of Vallorcine. **This map could be updated in the years to come and as the Sentinel-2 satellite mission progresses, in order to monitor changes in the area in the context of climate change and human activities (pastoralism, tourism, agriculture, etc.).**

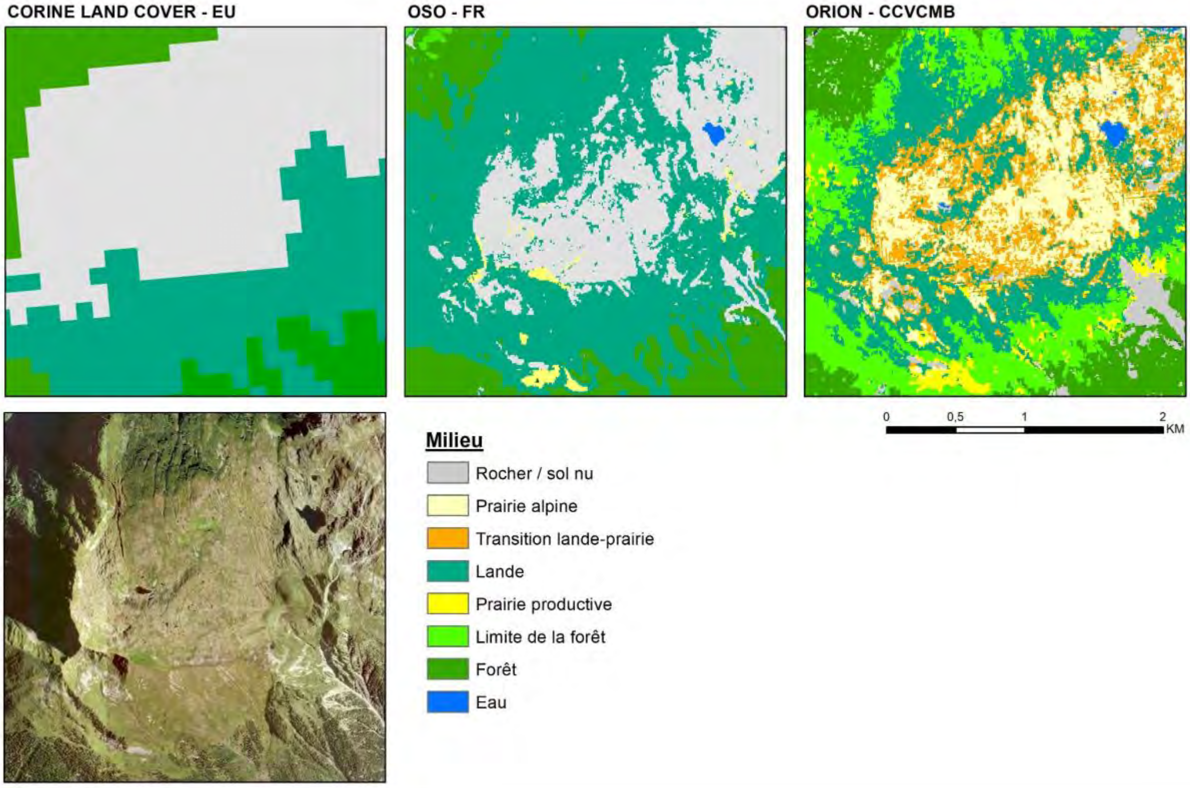


Figure 5B. Comparison of the ORION map with existing maps on a European scale (CORINE, resolution 100 m) and a national scale (OSO, resolution 20 m) for the Bellachat sector of the Aiguilles Rouges. The ORION map provides more information and precision than existing products, particularly in the context of alpine environments (moorland and grassland). **For the remainder of this report, the heathland class shown here in duck green will be shown in red to highlight the problem of heathland closing off open areas.**

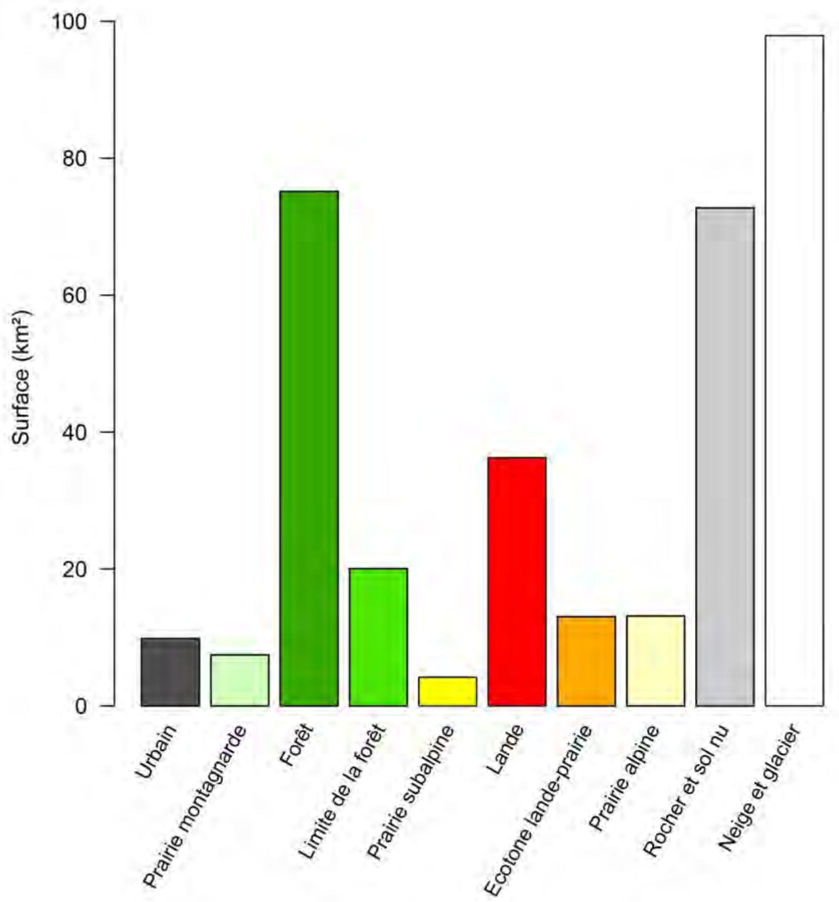


Figure 6. Distribution of surface areas for each habitat class on the territory of the CCVCMB, estimated for the period 2017-2021. Together, **sub-alpine and alpine grasslands, which are rich in biodiversity and ecosystem services, cover 5% of the CCVCMB territory.**

Validation of the habitat map

With regard to the first objective of the field campaign, **we found a high degree of consistency between the measurements taken in the field and the habitat map generated from satellite images** (Figure 7). It is important to note that the field surveys were carried out independently of the habitat map, i.e. the location of the surveys was chosen within each grid cell without consulting the habitat map beforehand. After extracting the habitat type for each vegetation survey, we quantified the frequency of the different vegetation functional groups according to habitat class (Figure 7). The result shows a high frequency of heathland in pixels classified as such, while the heathland-grassland class shows an interweaving of the three vegetation types. Pixels classified as alpine meadow show a peak in heathland near 0, with a higher frequency of forbs and graminoids. This result suggests that **moving from one habitat to another according to the satellite, for example from heathland to alpine meadow, involves functional changes** such as a drop in the quantity of forbs that constitute a resource of high forage quality for wild and domestic fauna (for example alpine clover or purple gentian).

We also extracted the vegetation height measurements for all the field surveys carried out above the forest (Figure 8). Here again, there is consistency between the habitat map and the structure of the vegetation measured in the field, with a decrease in height from the tall shrub and heath classes to the grassland classes. Figure 8 therefore also suggests a structural change in canopy height from one habitat class to another, which may have consequences for wildlife, domestic animals and humans off the trail. It should be noted that the "heath" class shows a high variability in height values, with measurements between 5 and 50 cm. This result suggests that it **would be interesting to**

try and split the current heath class into two, with a "high heath" class typically containing rhododendron and a "heathland" or low heath **class** characterised by other Ericaceae such as *Vaccinium* sp., dwarf azalea, callune or crowberry.

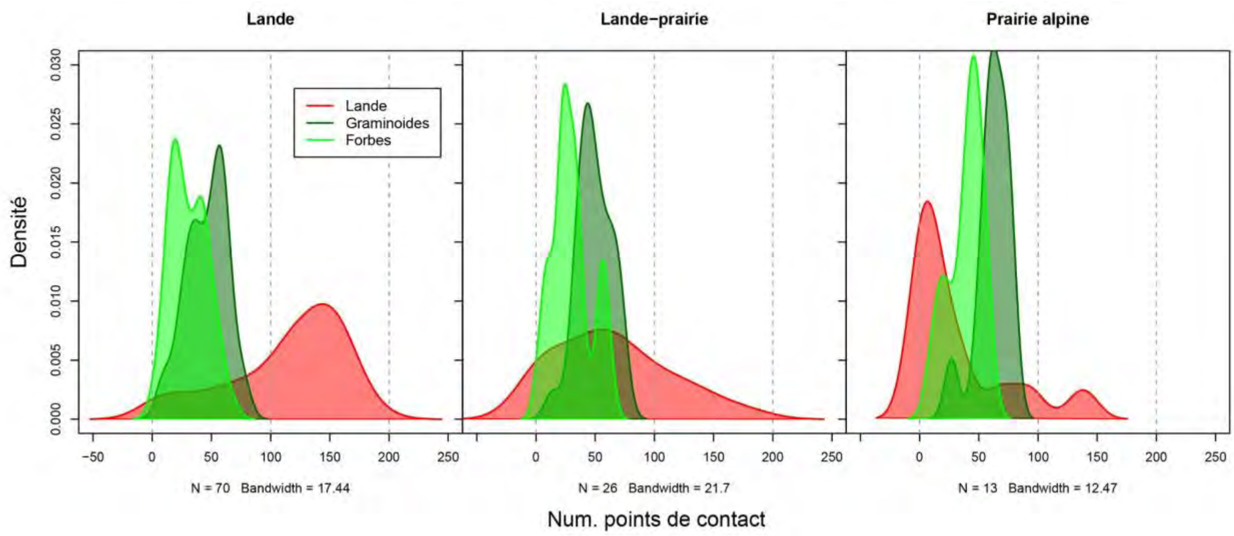


Figure 7. Density (or frequency) of vegetation functional group contact points as a function of the habitat class assigned by the model. The higher the value on the X axis, the more frequent the functional group is within the habitat. According to the field surveys, Ericaceae heaths are more frequent in the heath class, while forbs and graminoids are more abundant in the alpine meadow class of the ORION map.

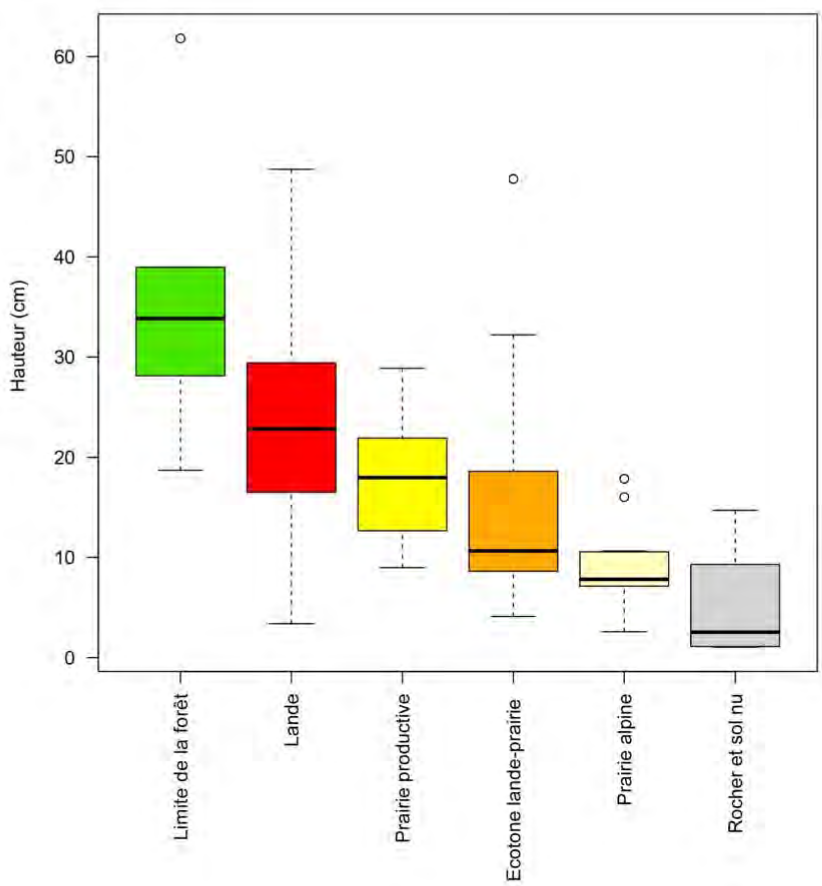


Figure 8. Boxplots of plant canopy height measured in the field (mean value per plot), as a function of habitat class. This result indicates that the habitat classes correspond to structural variations in habitats in the field, in this case canopy height.

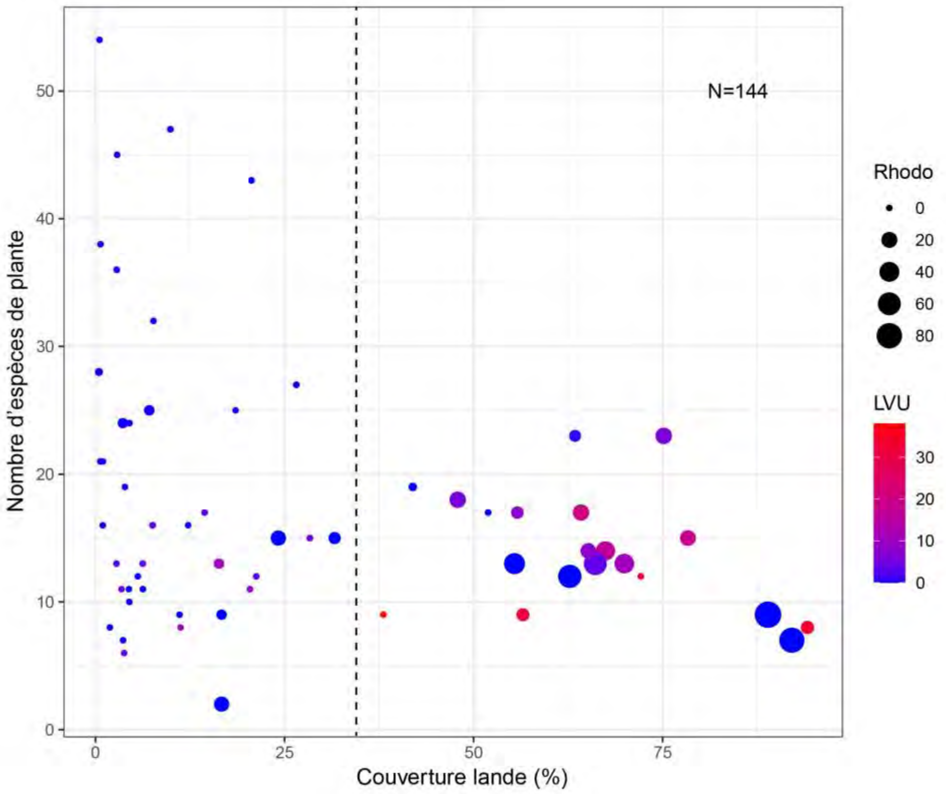
Implications of

heathland expansion for flora and fauna

Floristic diversity indicator

Figure 9 shows that when **heathland cover exceeds 30%, the species richness of vascular plants tends to decrease**. Most of the time, this drop in diversity is linked to a higher cover of either rhododendron ferrugineum (*Rhododendron ferrugineum) or blue* cranberry (*Vaccinium uliginosum),* or both. Another way of deepening this analysis at a later date would be to calculate other diversity indices such as Shannon, Simpson, etc. in order to better understand the consequences of heathland expansion on the structure of plant communities. It is also important to note that the quantity of species is only one indicator, and that forage quality is another important factor to be quantified in order to assess the consequences of heathland expansion on the resource available to herbivores, typically wild and domestic ungulates.

Figure 9. Variation in plant species richness as a function of moorland cover for 144 phytosociological surveys carried out by the CBNA above 1700 m in Haute-Savoie. The size of the dots corresponds to the percentage cover of rhododendron (Rhodo), while the colour corresponds to the percentage of blueberry (LVU). **A decrease in floristic diversity can be seen at heathland cover levels of over 30%.**



Indicators of favourable habitat for chamois and mountain hare

By analysing the images from the photo traps, we were able to see that the mountain hare tends to spend the winter in the forest to find shelter and food. However, in late spring and early summer, the species is most often detected in transitional areas between moorland and grassland (Figure 10). In fact, the species is never very present either in pure grassland, which may offer a quality food resource but leaves the hare exposed to predators, or in dense moorland, which probably makes it difficult for the animal to move around and offers a limited food resource. We hypothesise that a mosaic of heathland and grassland provides both protection against predators, thanks to the higher canopy of the heathland, and food, thanks to the greater resource present in the herbaceous environments. This result would therefore suggest that **maintaining a diversity of open and semi-open environments seems important for conserving the habitat of this species**, as has already been shown for other wildlife species such as the black grouse[18] . This type of analysis remains to be replicated for other species present in the CCVCMB area, such as the rock ptarmigan.

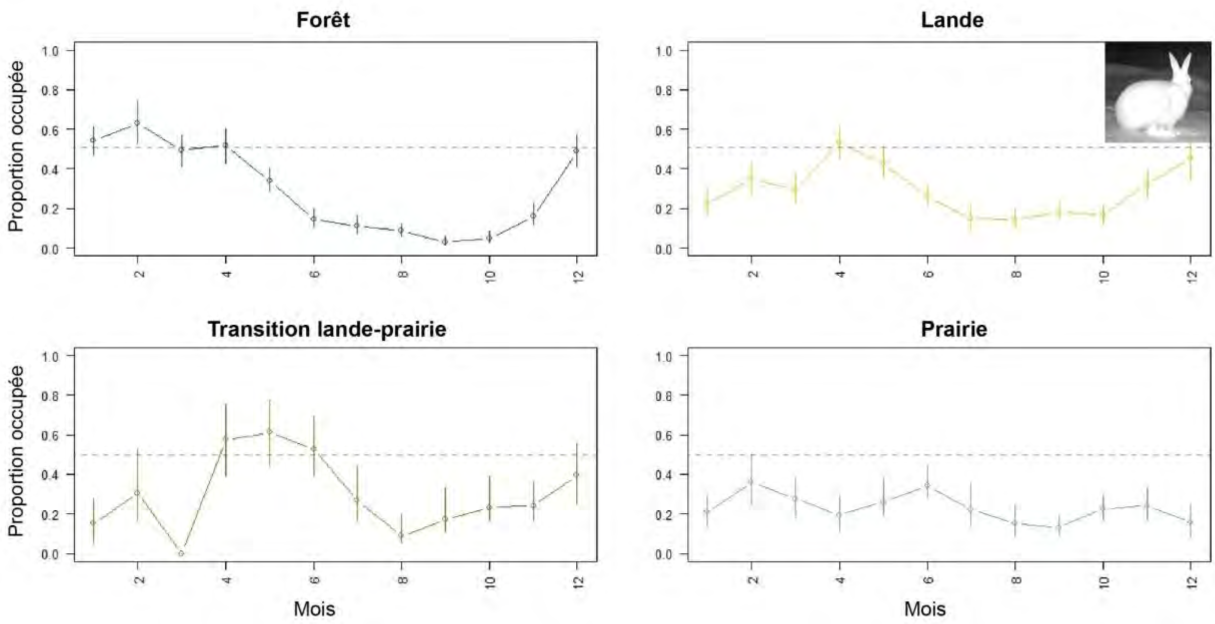


Figure 10. Proportion of photo-trap sites occupied by the variable hare as a function of month of the year and environment, estimated from a "site occupancy" model. The species seems to prefer to spend winter in woodland and summer in transitional areas between moorland and grassland.

We also analysed the habitat surveys in order to gain a better understanding of the interactions between vegetation structure and the frequentation of wild fauna, particularly chamois. Using photo traps, we found that chamois showed a lower probability of occupation in sites characterised by a greater height of vegetation, particularly above 40 cm (Figure 11). Given that rhododendron forms the tallest heathland canopies in the Chamonix valley, **this result suggests that chamois tend to avoid dense areas of rhododendron which are likely to hinder their movement and which are probably poor in terms of forage resources**.

The PCA analysis (Figure A4) shows fairly strong correlations between certain explanatory variables (SF-GDD and BI) and canopy height. We used this statistical relationship to generate a continuous map of canopy height values (Figure 12), which represents a first attempt to spatialise the functional properties of habitats. In the event, we did not find any statistical link between the explanatory variables we tested and different types of heathland (low heathland and rhododendron heathland in particular). For this reason, we stuck to our initial classification, which only identified heathland and heathland-prairie ecotone environments, without specifying different types of heathland.

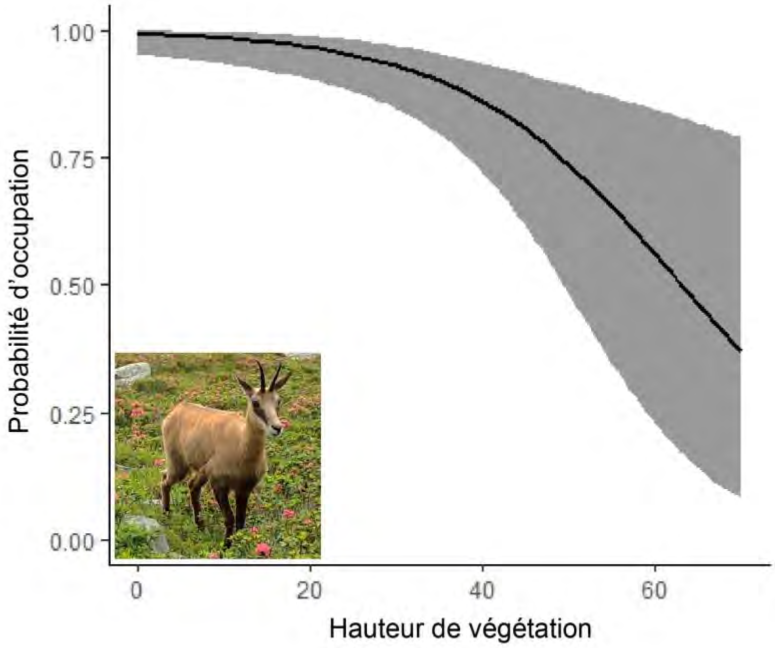


Figure 11. Occupancy probability curve (i.e. photo trap detection) for chamois as a function of plant canopy height. The statistical uncertainty of the curve is shown by the grey area, which indicates the standardised error.

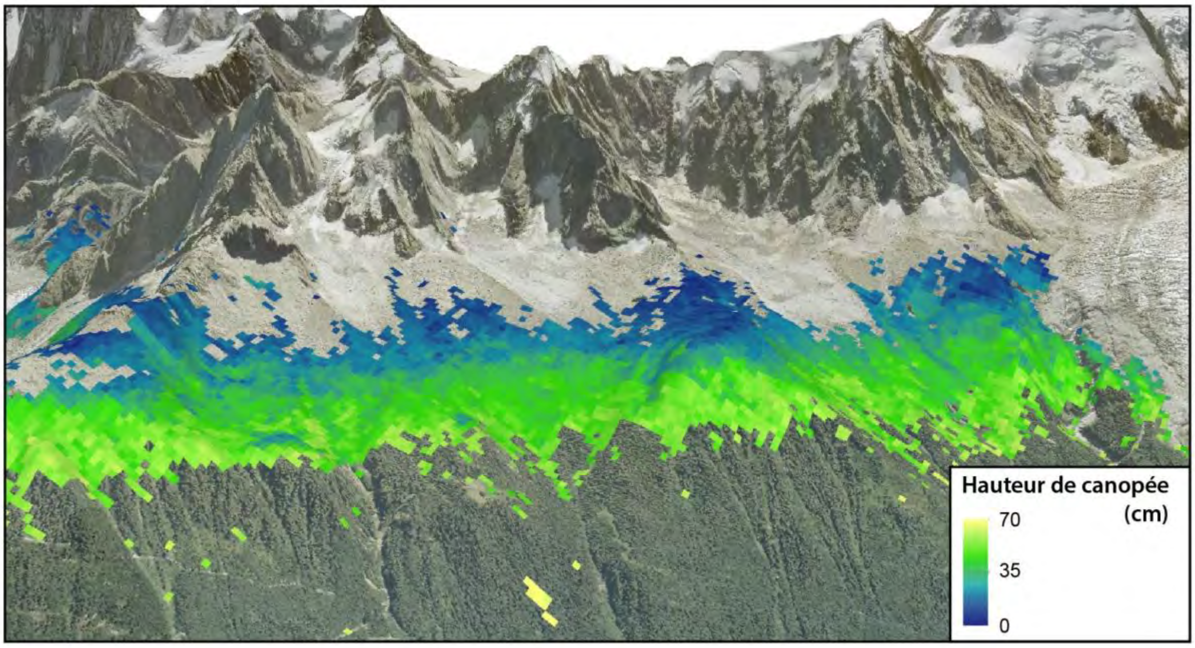


Figure 12. Predicted map of vegetation canopy height in the Plan de l'Aiguille sector, produced from a linear model between the mean height measured for each survey and the SF-GDD and BI. Figure A5 provides more statistical details on the model used to generate this map. This preliminary analysis raises the idea of modelling

the probability of occupancy of different species of large herbivores on the basis of spatial variables and in particular the functional properties of habitats (e.g. canopy height, forage quality or distance from forest or human activity hotspots).

IV. Perspectives for management and conservation

In order to make the results of the ORION project more operational for the managers of the Chamonix valley (CCVCMB and Asters), we have zoomed in on a number of issues and areas where there is a great deal at stake for the region. **The objectives identified are as follows: to conserve the diversity and pastoral resources in the mountain pastures and high-altitude meadows, to monitor changes in habitats within the nature reserves, and to promote a balance between wildlife and human activities** (Figure 13). We assume that more precise monitoring of the evolution of natural and semi-natural environments could facilitate and inform decision-making in the coming years with a view to achieving these objectives.

Figure 13. Photo trap of sheep surprised by chamois in the Peclerey mountain sector. We hypothesise that the limited area of grassland in the CCVCMB, which is likely to diminish still further in the face of the rise of trees and the expansion of moorland, is intensifying competition for resources between wild and domestic ungulates.

Identification of high-stake areas in the Chamonix valley

Mountain pastures

We have extracted the habitat map for each mountain pasture in the Chamonix valley, classifying them from most to least overgrown (Figure 14). There is a strong gradient between the Blaitière mountain pasture, which is almost entirely colonised by moorland and forest, and the Bellachat mountain pasture next to Le Brévent, which remains mainly grassland. In some mountain pastures, such as Balme, Le Lavancher and Loriaz, the areas of sub-alpine meadows in yellow are surrounded by moorland and the forest limit, which suggests that pastoral activity (past and present) maintains these areas of meadows in places that would otherwise be colonised by woody plants (trees and shrubs). It is interesting to note that if you only look at the aerial photo of these mountain pastures (Figure A6), with the naked eye it is possible to distinguish only woodland vegetation from non-forest vegetation, which underlines the usefulness of the ORION map in being able to differentiate between supra-forest areas of grassland and heathland.

To take the analysis further, we distinguished between "grazeable" and "non-pastureable" habitat classes. We considered that grazing is possible in montane grassland, subalpine grassland, heathland-grassland ecotones and also in alpine grassland. In this case, it is considered that forest and forest edge areas, continuous moorland areas or areas of rock and bare ground provide an insufficient resource to support grazing activity. This distinction is necessarily simplistic, and ignores the presence of herbaceous plants within the heathland (Figure 7) and also the possibility of undergrowth grazing (but it seems to us that this form of grazing is very little practised in the CCVCMB). Thanks to this approach, **we can quantify an "area suitable for grazing" indicator for each mountain pasture (Figure 15), which represents a percentage of the area suitable for grazing**. This area is likely to change according to the grazing load allocated during the year, the type of livestock, and also any scrub clearance undertaken by the shepherds and/or managers. In this way, this indicator could serve as a gauge of the conservation of existing alpine pastures, as well as the restoration of alpine pastures that are currently largely enclosed by ligneous vegetation.

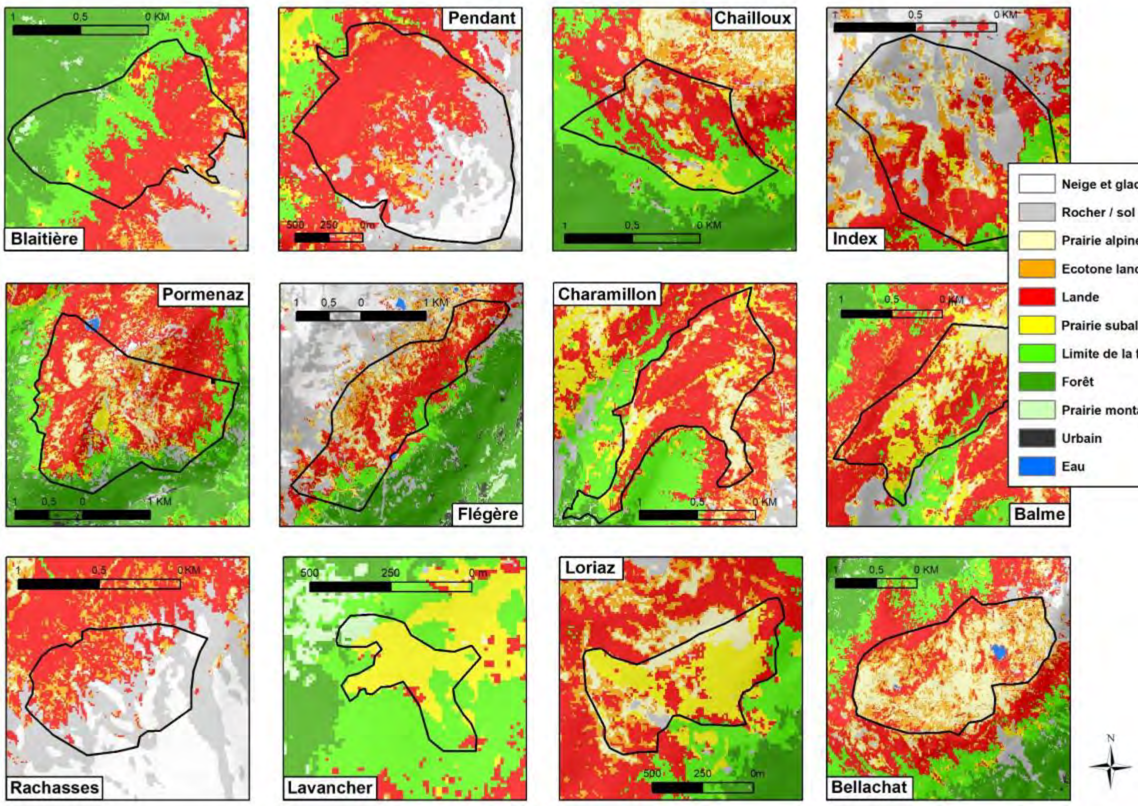


Figure 14. Extracts from the habitat map for each mountain pasture in the CCVCMB. The Blaitière, Pendant and Rachasses mountain pastures have very little continuous grassland, although graminoids and forbes are certainly intermingled in the heath and provide a certain pastoral resource (Figure 7). In this case, the Bellachat, Loriaz

and Le Lavancher mountain pastures have large areas of grassland. We can deduce that these meadows are maintained by historical and current pastoral activity since they are surrounded by moorland, forest or both.

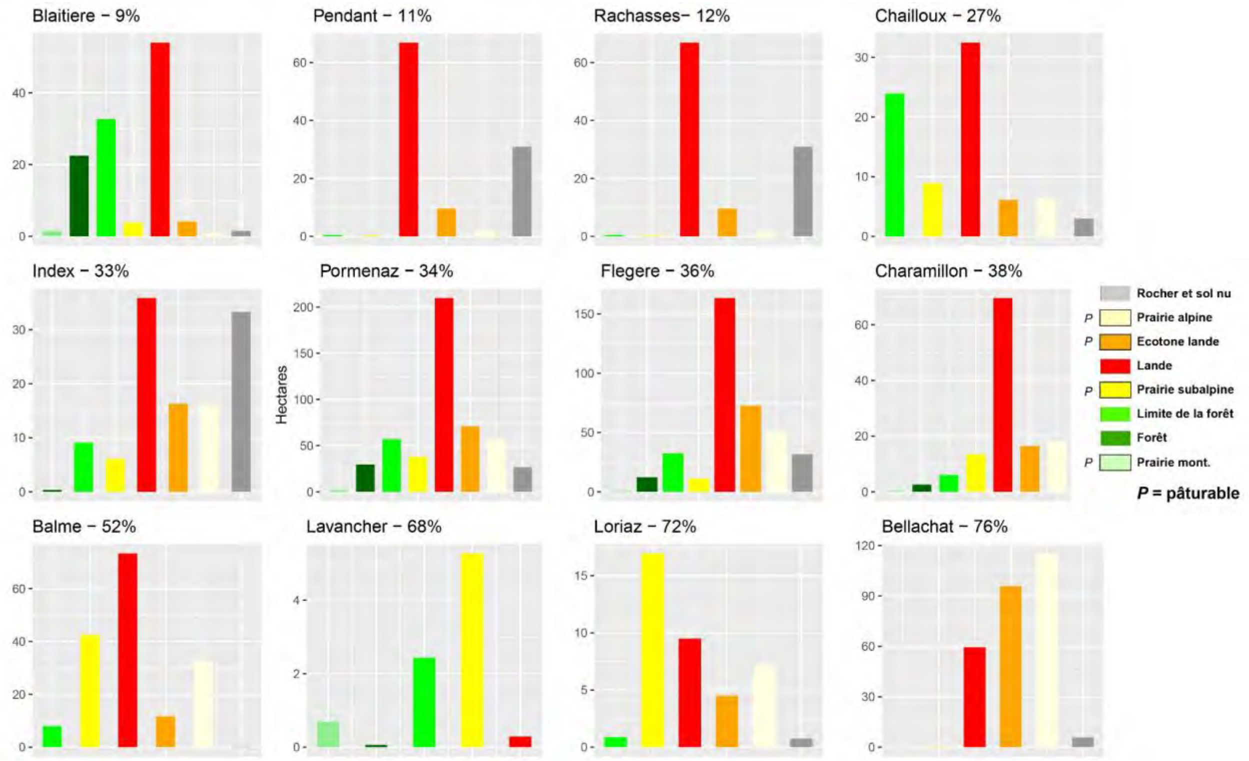


Figure 15. Distribution of the surface area of the different habitats present in the mountain pastures of the CCVCMB. The "grazeable area" is defined here as the sum of the following habitats: montane meadows, sub-alpine meadows, heathland-meadow ecotone zones and alpine meadows. **Heathland is the dominant habitat on all the mountain pastures in the CCVCMB, with the exception of Le Lavancher, Loriaz and Bellachat.** The area available for grazing could become an indicator to be quantified in the years to come in order to monitor and better understand the evolution of the mountain pastures in relation to pastoral activity (or lack of it) and climate change.

Nature reserves

The primary vocation of the valley's nature reserves is to protect biodiversity and its free evolution, with a minimum of interference from human activities. In this context, **the ORION map could be used above all to monitor and quantify the trajectories of the various habitats being protected, and to gain a better understanding of their rate of change, particularly in the face of climate change.** However, if the aim is to conserve certain highly diverse open environments (snow-comb grassland, the flora of alpine wetlands, or species-rich mesophilic alpine meadows, for example), or a habitat that is favourable to wildlife that needs a semi-open mosaic habitat to function properly (such as the black grouse), then the ORION map could be used to validate the effectiveness of the conservation measures put in place. We can also imagine **cross-cutting issues between pastoralism and conservation, for example at the Bellachat mountain pasture** in the Carlaveyron reserve (Figure 16), the largest mountain pasture in the Chamonix valley and an important area for wildlife.

Today, the Chamonix nature reserves are home to a high diversity of environments, with very little grazed subalpine meadow but otherwise a good distribution of other natural habitats (Figures 16-17). Heathland is the dominant habitat in the Aiguilles Rouges reserve, while forest is dominant in Carlaveyron and the bare ground of high mountain environments (scree, scree slopes, rock faces) represents the largest surface area in the Bérard valley.

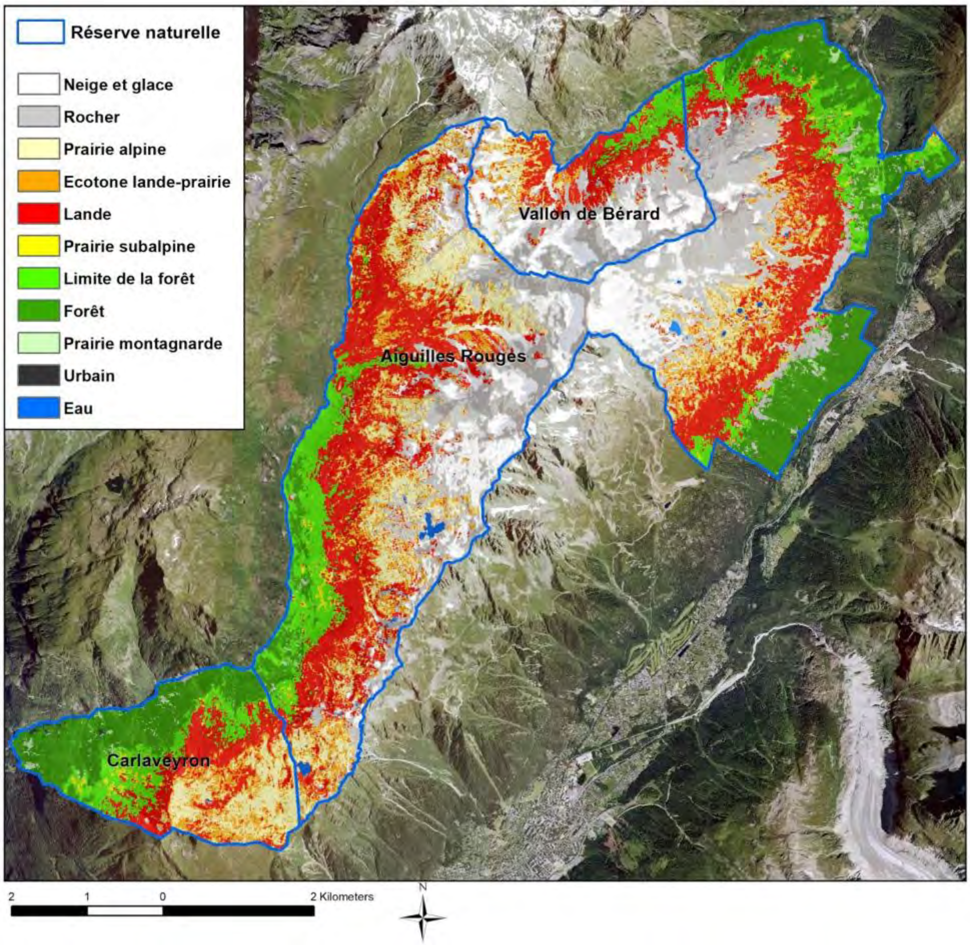


Figure 16. Extract from the map of habitats within the perimeter of the CCVCMB nature reserves.

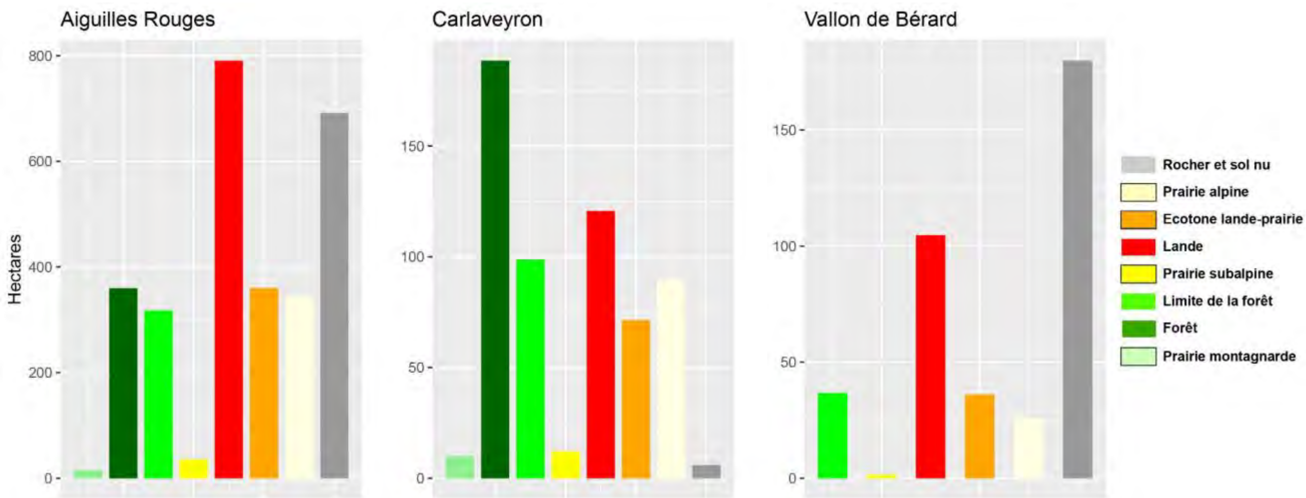


Figure 17. Distribution of the surface area of the various habitats present in the CCVCMB nature reserves. As with the mountain pastures, **updating the ORION map could be used to monitor changes in habitats over the coming years** and possibly identify areas where certain critical habitats, such as alpine meadows, are in decline.

Towards seasonal maps of habitats occupied by wildlife

The network of photo traps installed by CREA Mont-Blanc in the Chamonix valley enables us to observe the invisible: discreet species that are active at night and dawn and avoid human presence. This valuable information provides a better understanding of the behaviour of wildlife and their use of habitats over the seasons, as shown in Figure 10 for the mountain hare. One limitation of this approach is that observations are restricted to the locations where the cameras are installed. In this context, the ORION map can provide a complementary tool that makes it possible to move from the local scale to the landscape scale and to "spatialise" the results observed by camera traps.

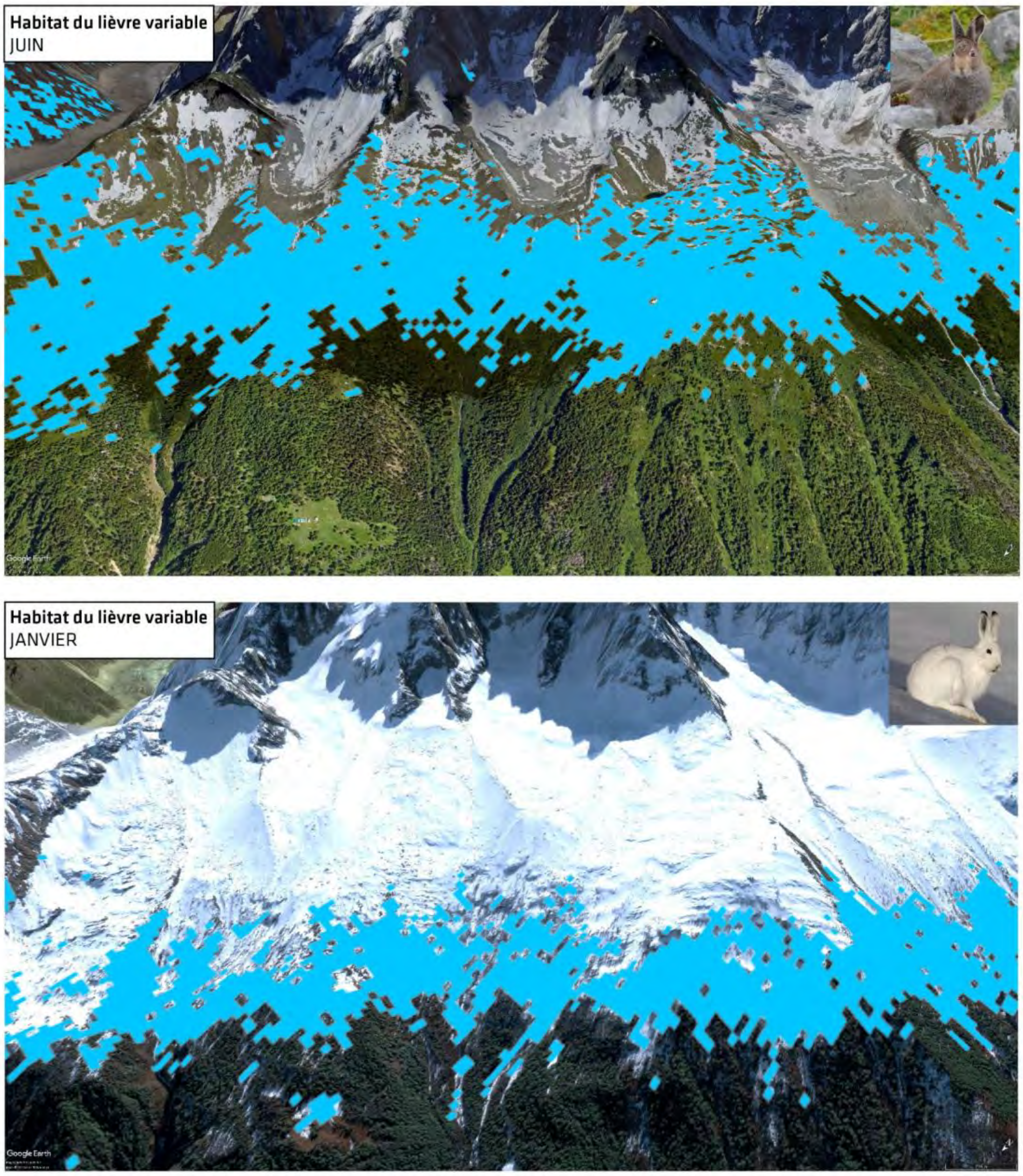


Figure 18. Seasonal maps of the majority habitat of the mountain hare, shown in blue. By majority habitat we mean the habitat where the species spends most of its time, although it is always possible that it frequents other habitats. As shown by the photo traps (Figure 10), the hare tends to spend the winter on the edge of the forest and then climb in altitude to spend more time in mixed moorland and grassland environments in spring and early summer. **The ORION map can be used to spatialise the spot observations made using photo traps at landscape level.**

Figure 18 provides an initial overview of this approach for the mountain hare, based on the observation that the hare tends to spend winter in woodland and early summer in heathland-grassland ecotones. **This approach would make it possible to cross-reference the majority habitat areas of the hare (or other species) with spatial data that locate different human activities (pastoral and tourist), with the aim of promoting a balance between these different uses of the landscape and over the seasons**. In a context where constraints are increasing for wildlife (global warming, the arrival of more competitive species at lower altitudes such as the European hare, greater use of the mountains by sports enthusiasts), it seems all the more important to have precise spatial and temporal tools at our disposal in order to optimise conservation measures, always in balance with the region's tourism requirements. Having maps of the main habitats for the mountain hare and other sensitive species would also be a way of making mountain walkers aware of the areas that are sensitive for wildlife, beyond the designated quiet zones and depending on the season[19] .

V. Conclusion: the ORION map, a new tool for monitoring the territory

In relation to the initial aim of gaining a better understanding of the expansion of heathland in the CCVCMB area, the ORION project has provided a number of tools for managers of natural areas. Firstly, we have produced a high-precision map (10 m) that distinguishes heathland from other habitat types (grassland, forest and transition zones). In our opinion, this mapping is far superior to existing products on a French (OSO) or European (CORINE) scale, thanks to the selection of explanatory variables used, the local calibration of the algorithm in the Chamonix valley and also the habitat classes modelled, which include transition habitats (forest limit and heathland-grassland ecotone). Secondly, we assessed some of the ecological consequences of the expansion of heathland in terms of i) the diversity of flora in an open environment at altitude, and ii) the availability of the main habitat for certain wildlife species (chamois and mountain hare). We have also identified certain areas where there are major management and conservation issues, in particular mountain pastures and nature reserves.

Finally, we have made these tools and indicators available on the Mont Blanc Atlas website, a showcase for the ecological changes underway in the Mont Blanc massif:

- through **an "Issues" page** entitled Alpine meadows, pockets of resistance, which presents the unique profile of the Mont-Blanc massif and the scarcity of the surface area occupied by meadows,
- through **an "Indicator" page** entitled Satellite monitoring of a "grazable area", which presents the "grazable area" indicator

These two pages are linked together by hyperlinks, allowing you to move from the presentation of the major issues to the details of the monitoring method used, and vice versa (Figure 19). They are the result of a tailor-made rewrite, in order to present the results of the ORION project in a way that is **consistent with the editorial line of the website.** Graphic work was also carried out to produce an attractive visual resource that could be distributed in image form, presenting the different habitat classes in the massif and the proportion of "grazeable area" in a selection of mountain pastures. In addition, web integration work was carried out **to make the habitat class map available interactively** (Figure 20), based on an OpenStreetMap map.

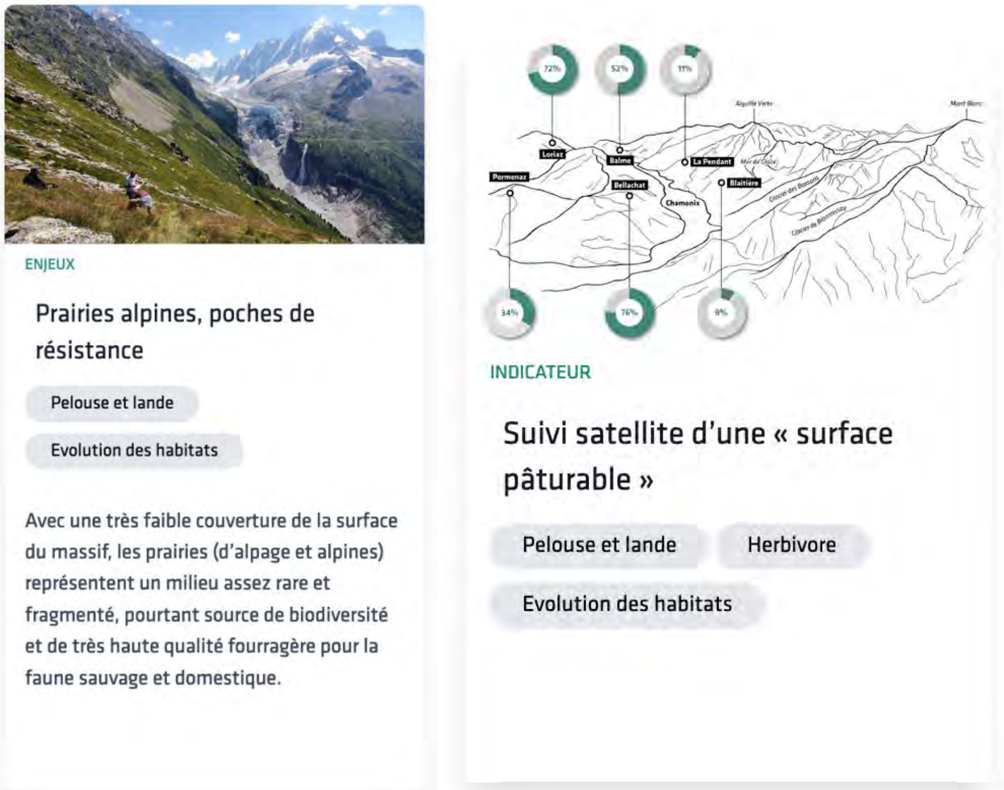


Figure 19. Screenshots of the illustrative thumbnails of the two pages concerned on the Mont Blanc Atlas: on the left, the "Issues" page; on the right, the "Indicator" page. These two pages are linked by clickable hyperlinks.

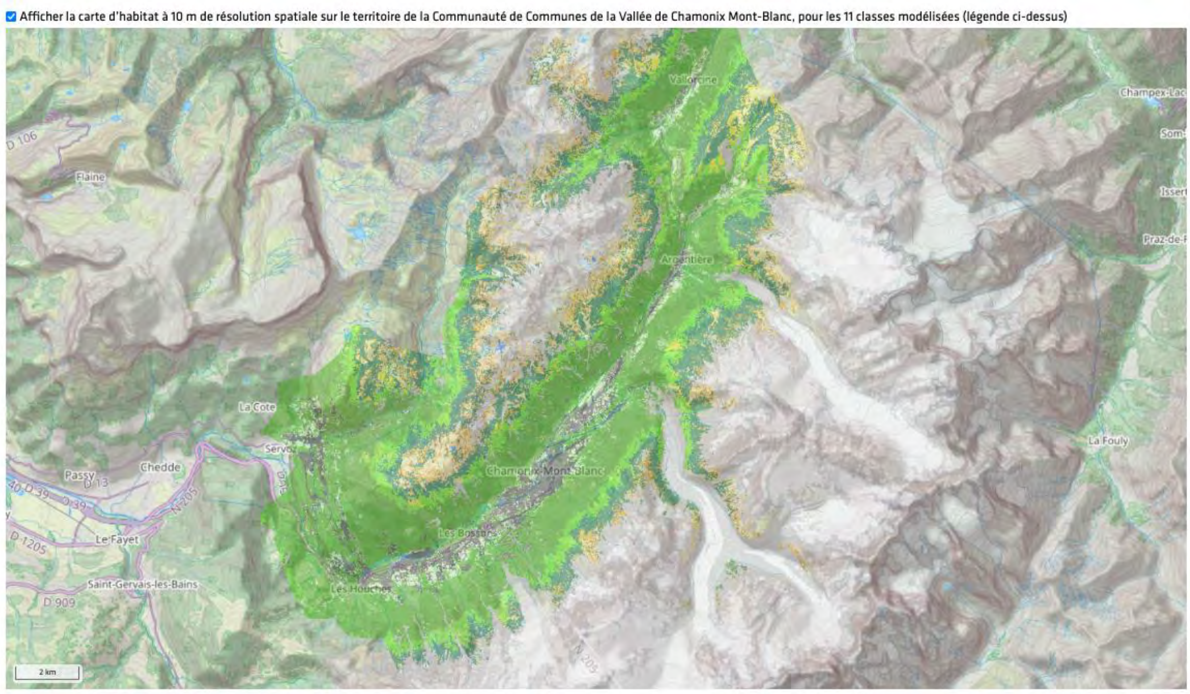


Figure 20: Final habitat map at 10 m spatial resolution for the CCVCMB territory for the 11 classes modelled, displayed interactively on the Mont Blanc Atlas, on an OpenStreetMap map base.

The main contributions of the project to the region can be summarised as follows:

1. **Decision-support tool for mountain pasture management**
2. **A tool for monitoring changes in habitats, particularly in nature reserves**
3. **Conservation tool for sensitive wildlife species** (mountain hare in a initially, but may be extended to other species)

The next step will be to integrate the tools produced by the ORION project into an adaptive management and monitoring approach. Adaptive management combines scientific knowledge (or the need for it) with management objectives, with the aim of defining relevant management actions and measuring their effectiveness using ecological indicators (Figure 21)[20] . The ORION map could be used to consolidate this approach in the years to come, in addition to other information (climate and usage data, or wildlife activity data). In general, the adaptive approach can be broken down into four stages[21] :

1. **Defining the problem**
2. **Articulating the associated management objective**
3. **Identify possible actions, consider their potential ecological consequences and choose which one(s) to implement**
4. **In the light of one or more ecological indicators, assess the effectiveness of the management actions implemented and adjust them if necessary**

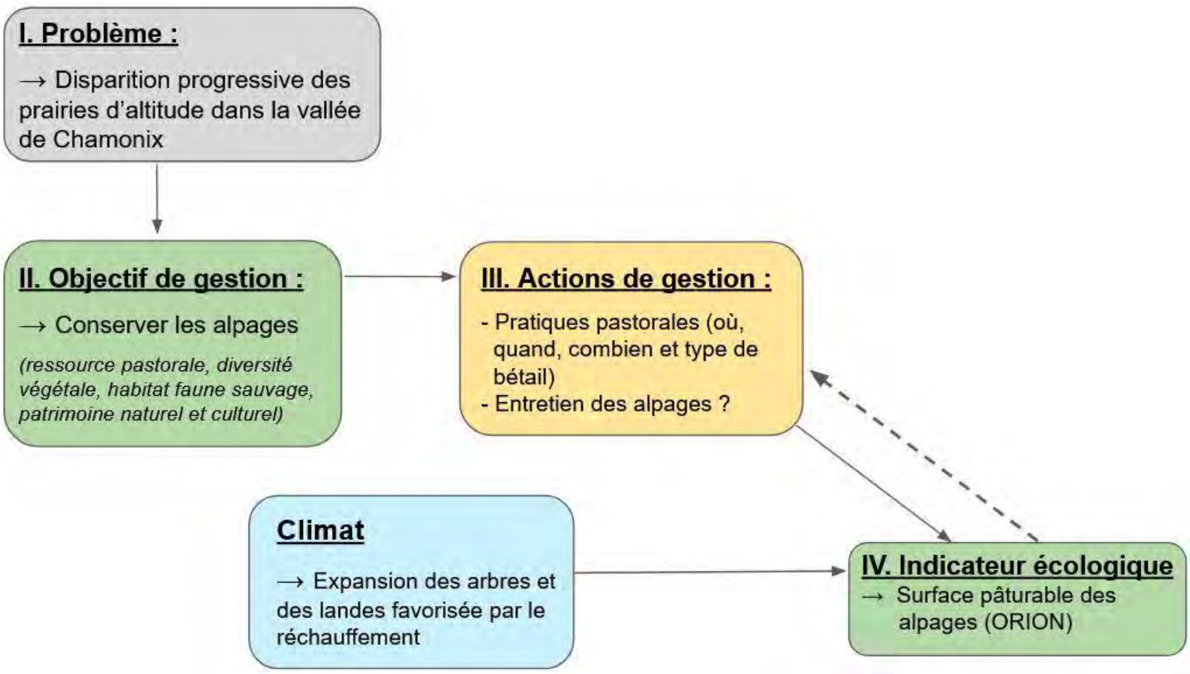


Figure 21. Diagram showing an example of an adaptive monitoring approach for mountain pastures in the Chamonix valley, with the aim of preserving the valley's remaining high-altitude meadows. **A "grazeable area" indicator would make it possible to assess the effectiveness of management measures, and also to take account of changes in the environment in the face of climate change**. The dotted arrow indicates the adaptive loop, in which the indicator is used to inform decision-making and adjust management actions if necessary. It should be pointed out that this diagram is hypothetical and serves to illustrate the approach; it would be necessary to validate these objectives with the managers and ideally to quantify the historical dynamics of the area of grassland in the Chamonix valley in order to better contextualise the problem of the regression of grassland.

The progress made by the ORION project could also be used to inform the cross-border sustainable development efforts being carried out in the Espace Mont-Blanc between Haute-Savoie and Savoie (FR), the autonomous region of the Aosta Valley (IT) and the canton of Valais (CH). The issue of heathland expansion addressed in this report is also relevant on the Swiss and Italian sides of the massif, particularly in relation to the objectives of conserving biodiversity, maintaining pastoral activities and also seeking a balance between tourist numbers and the preservation of wildlife. The increase in forest cover at the expense of high altitude open areas is also a major issue for the whole region, as identified in the EMB's climate change roadmap. Finally, the ORION map applied to the EMB would enable monitoring of changes in the glacial surface and ecosystems emerging as a result of glacial retreat in high mountain environments.

Although they represent significant methodological advances, the current maps of the natural environments of the Chamonix valley and the Espace Mont-Blanc are of limited interest given the current situation. We are convinced that the regular updating of the maps throughout the Sentinel-2 satellite mission, using the model calibrated in this project, will enable precise monitoring of the evolution of habitats and a better understanding of their dynamics in the face of climate change and in relation to human activities in the years to come. The introduction of ecological indicators, for example in relation to pastoral management, would make it possible to assess the effectiveness of the management measures undertaken as part of an adaptive management approach. **In our view, this is a high-potential tool, mobilising cutting-edge academic knowledge for the benefit of local stakeholders**. Finally, we recommend that cross-analyses be continued between the observation of fauna using photo traps and the characterisation of favourable habitats at landscape level using ORION, both by applying the approach to other species (e.g. the ptarmigan or the chamois) and also by integrating functional properties such as the height of the vegetation, the quality of the forage resource or human frequentation in space and time.

VI. Communication about the ORION project

Thanks to the support of the SCO France team, the project has benefited from the following communication media:

- Video explaining the project
- Project description page on the SCO France website
- Article on the kickoff meeting for the project in autumn 2021
- Presentation of the project at the Quarterly Meeting of SCO Projects on 27/9/2022

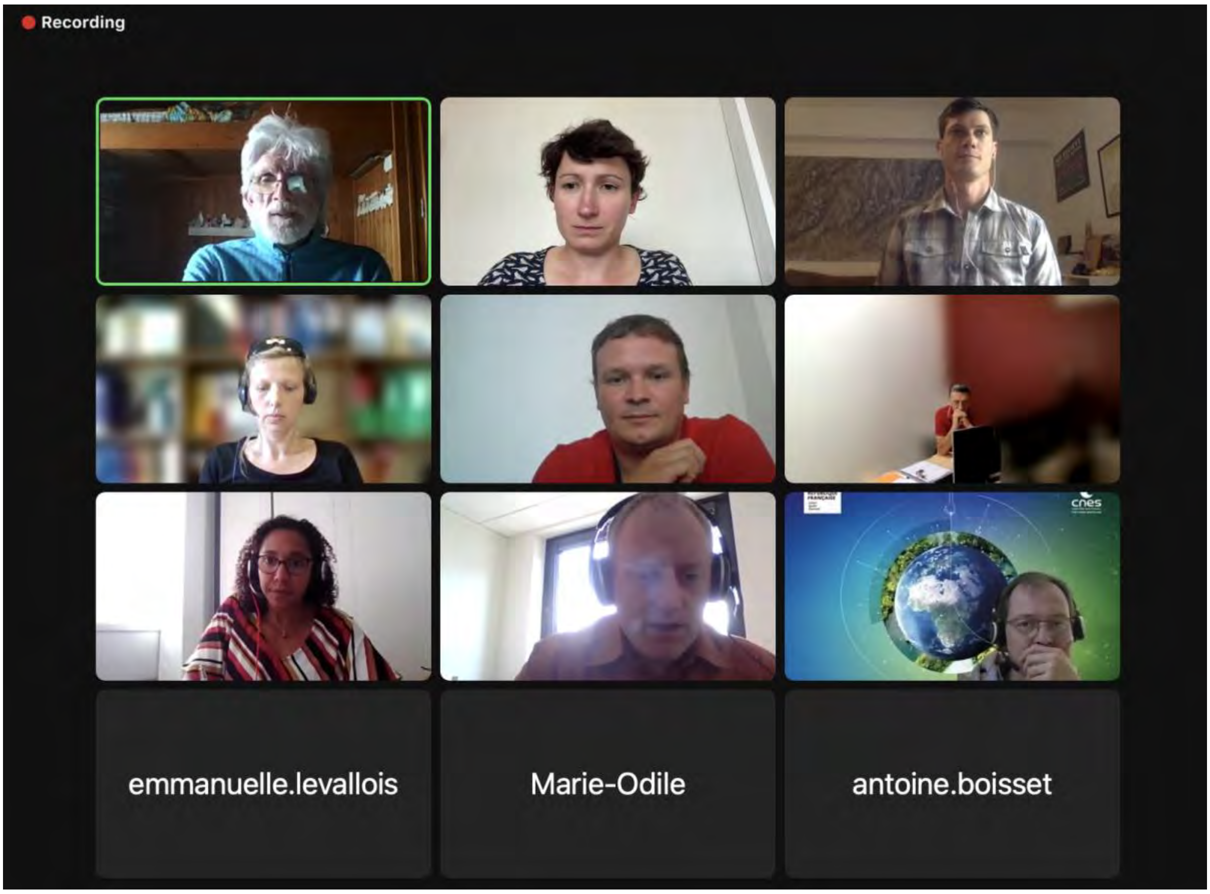
Other presentations of the ORION project were given:

- As part of Space Week organised by LYNRED on 06/10/2022
- At the PASTORAL scientific conference at the Fort de Bard on 16/3/2023
- On the CREA Mont-Blanc corporate website

We also took part in several discussion meetings with Asters and the CCVCMB in order to adapt the project to their needs and keep them informed of the results:

- Kick-off meeting on 16/11/2021
- Monitoring committee meeting on 8/11/2022

- Report to the CCVCMB on 28/6/2023
- WindUp Meeting, final report bringing together all project stakeholders, 20/09/2023 (read the questions and answers put during the meeting)



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IX. Appendices

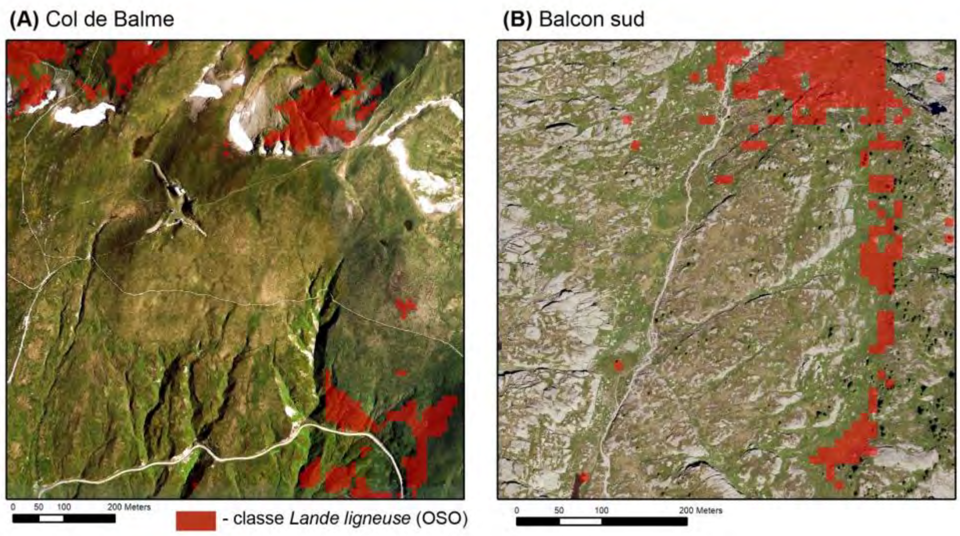

Figure A1. Examples of THEIA's OSO land cover product for the "woody heath" class (shown in red) at **(A)** Col de Balme and **(B)** on the S balcony of the Aiguilles Rouges. Many patches of heathland, corresponding to dark green areas, are not detected by this classification, hence the need to improve the tools available to managers and decision-makers.

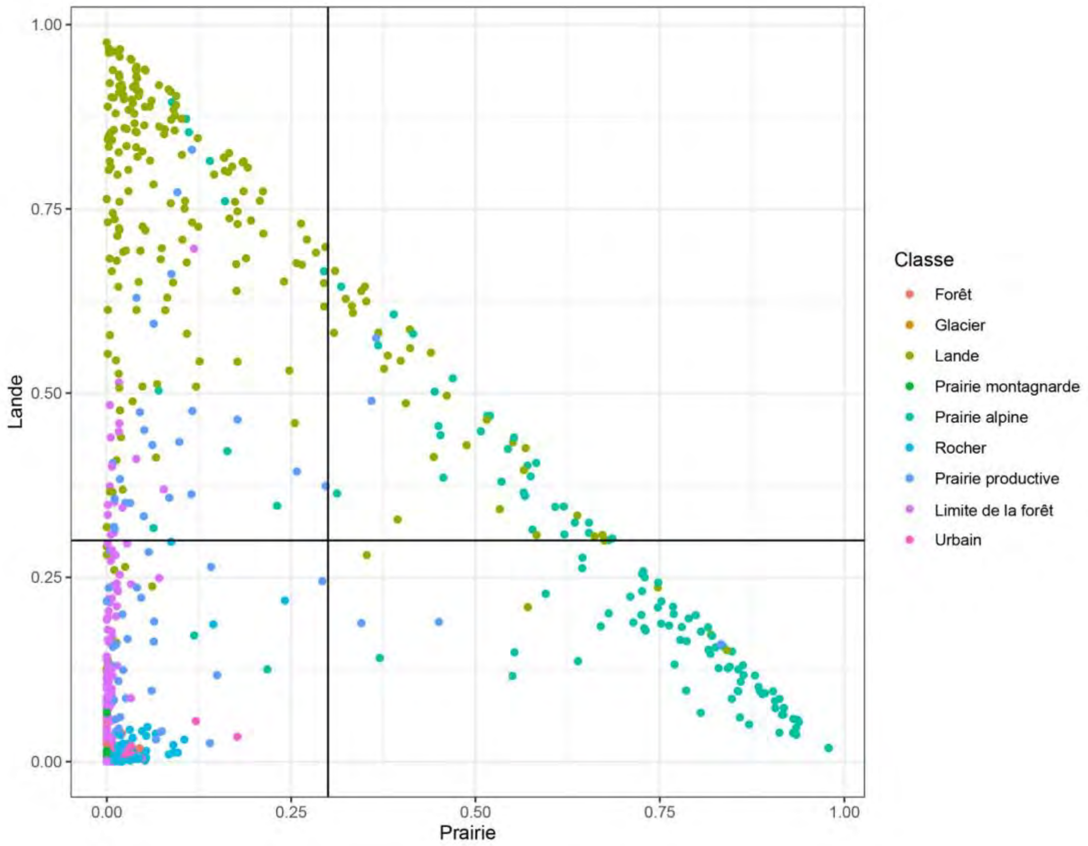

Figure A2. Plot of probability of classification as grassland vs. heathland for all training points (N = 883). The lines indicate probability thresholds of 0.3: if the model predicted a probability value greater than 0.3 for both heathland and grassland, we assigned the pixel to a new "heathland-grassland ecotone" class (Figure 4).

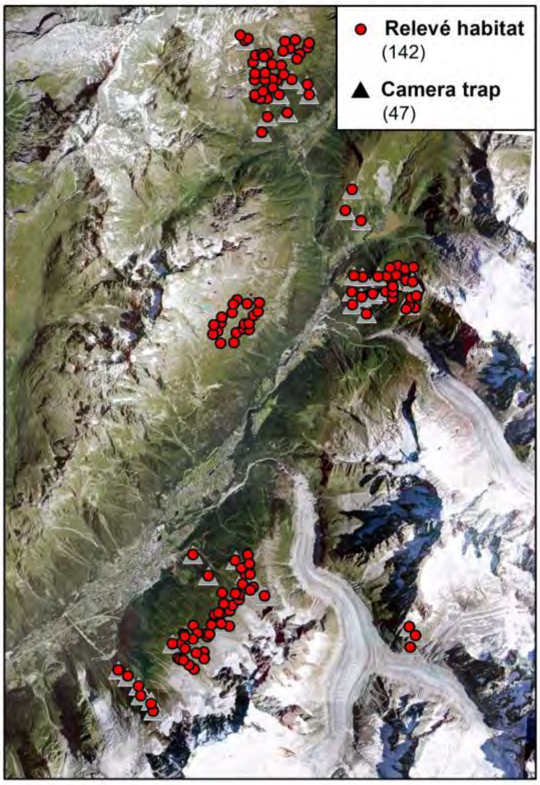

Figure A3. Location of the 142 habitat surveys carried out in summer 2022 (red dots) and the 47 photo traps (grey triangles) installed between 2018 and 2022. We carried out the habitat surveys systematically in front of the photo traps (in the shooting zone), and also within a 250 x 250 m grid in order to ensure spatial distribution between the surveys.

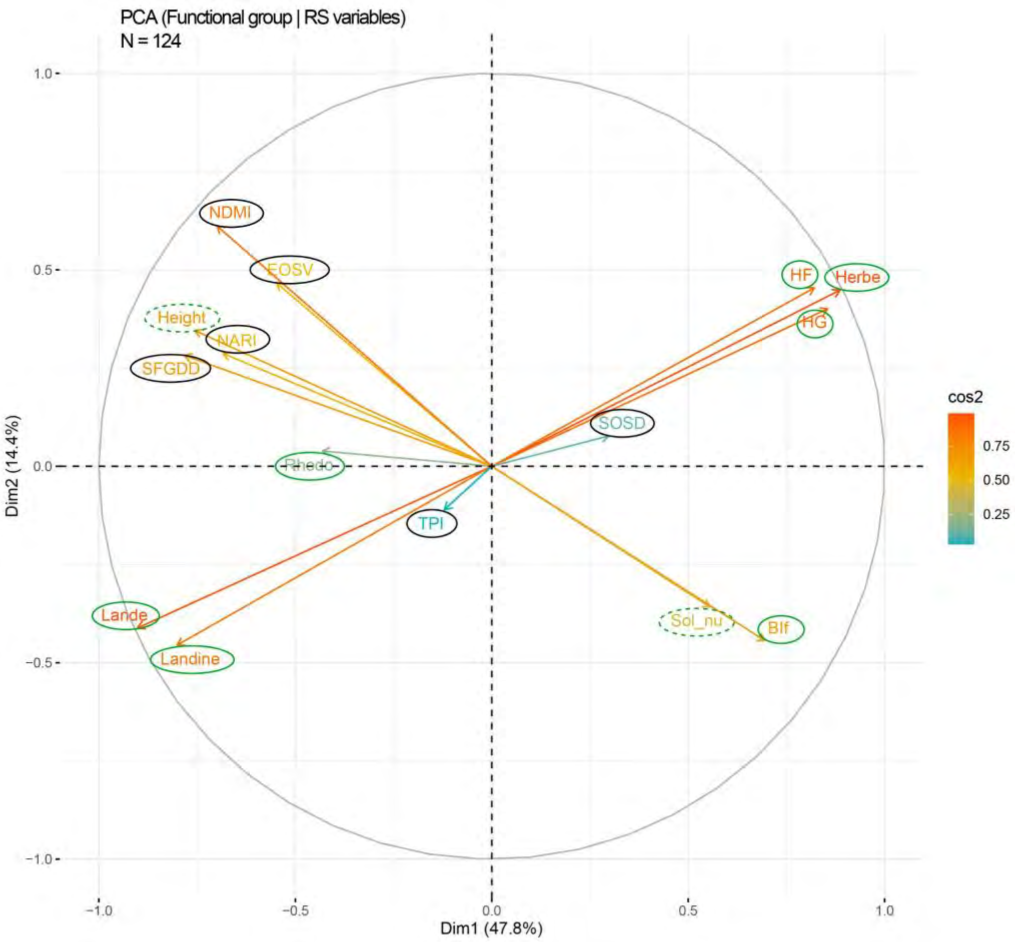

Figure A4. Correlation circle between the spatial explanatory variables (Table 1) and the functional groups and properties of vegetation measured in the field, derived from a Principal Component Analysis (PCA). It should be noted that the explanatory variables SF-GDD, NARI and BI are strongly correlated with vegetation height, which makes the modelling shown in Figure 12 possible. However, none of the explanatory variables is correlated with the functional groups of high rhododendron heath and low *Vaccinium* spp. heath, which discouraged us from trying to model several types of heath.

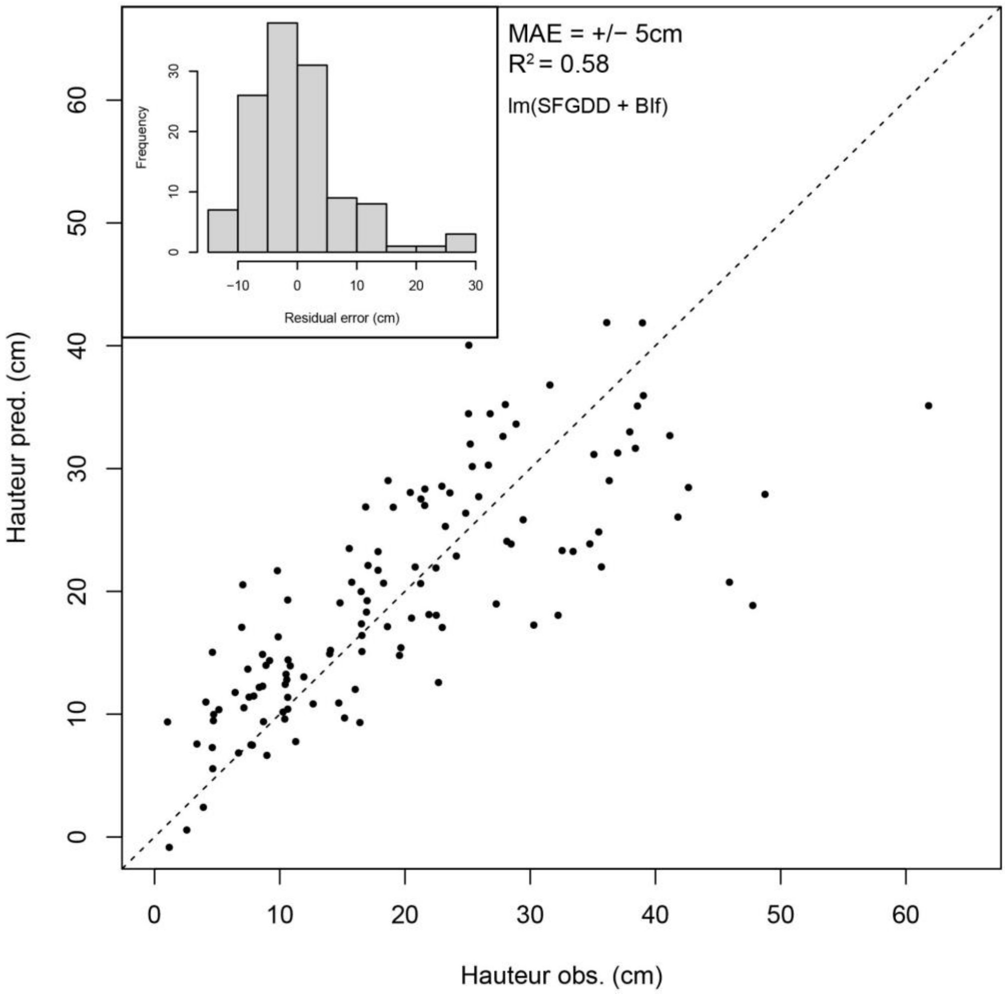

Figure A5. Bi-plot of vegetation canopy height observed in the field and predicted by a linear model based on the sum of the degrees of snow-free days (SF-GDD) and the ground luminosity index (BIf). The error is well distributed, with the exception of a few points with a high observed height that show a strong positive residual. These points should be examined further to better understand the reasons for these discrepancies.

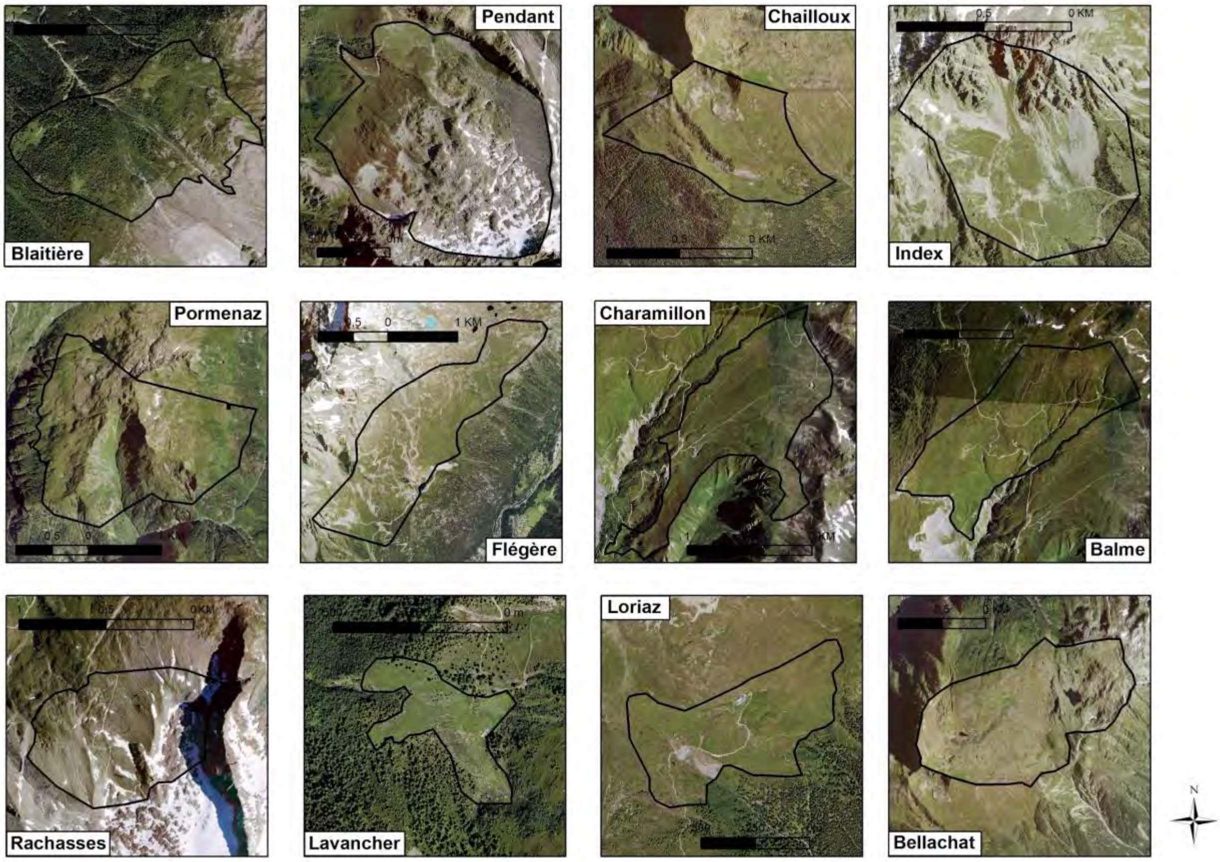

Figure A6. Aerial photos of the various alpine pastures in the Chamonix valley to complement figures 14-15.

	Mean Decreasing Accuracy	Mean Decreasing Gini
SFGDD	0,21	141,60
BI	0,20	120,66
NDMI	0,15	107,92
SOSD	0,16	103,48
NARI	0,13	100,49
EOSV	0,12	92,60
DAH	0,04	48,58
TPI	0,02	36,22

Table A1. Explanatory variables classified according to their predictive capacity (Accuracy and Gini coefficient), all classes combined.

Appendix S1. Calculation of degrees of snow-free days (SF-GDD)

In order to estimate the bioclimatic variable SF-GDD, we cross-referenced two sources of information: snow duration maps generated by the CESBIO from time series of Landsat and Sentinel-2 images and available on the THEIA cluster website[11] , and temperature series modelled for the French massifs by Météo-France and the Centre d'Etudes de la Neige[12] . The first step was to download the snow duration maps (SMOD) for the Espace Mont-Blanc region and for each year from 2017 to 2021. Then, using the average daily temperatures, the following calculation was carried out for each pixel in the study area: extract the first day without snow, and then add up the daily temperatures above 0°C from that date until 31 July. From the five annual rasters of the sum of degrees of snow-free days (SF-GDD), we calculated the average SF-GDD value for each pixel. This last map was used as an explanatory variable in the habitat prediction model.

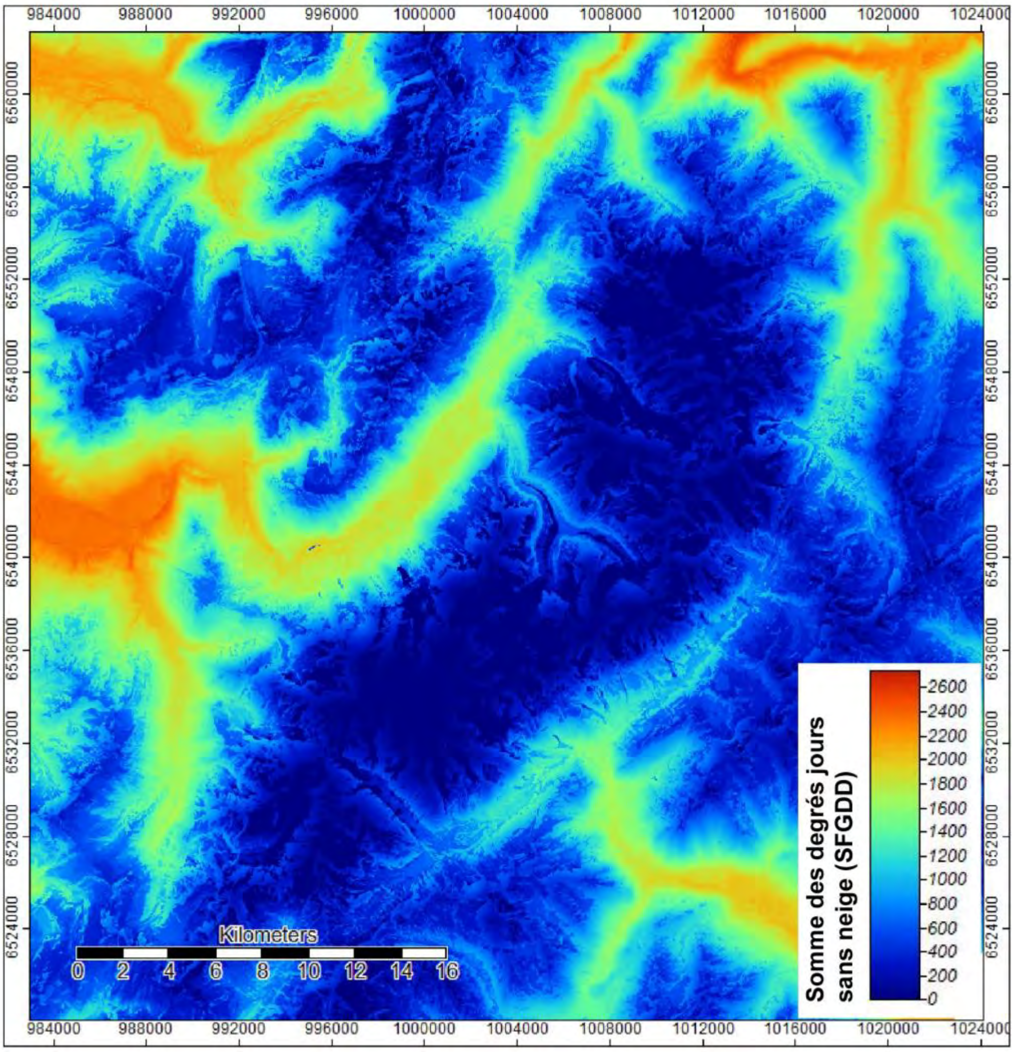

Figure A7. Example of a map of snow-free degree days in the Mont-Blanc massif for 2018. The number of degree days available is strongly linked to altitude, but also to topography (moraines, ridges, etc.) and areas where snow is deposited by avalanches, as can be seen in the couloirs at the foot of the south face of Mont Blanc.