Biogeosciences, 21, 2717–2730, 2024
https://doi.org/10.5194/bg-21-2717-2024

Biogeosciences
Open Access

Remote sensing reveals fire-driven enhancement of a C_4 invasive alien grass on a small Mediterranean volcanic island

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Received: 27 January 2023 – Discussion started: 21 March 2023
Revised: 3 April 2024 – Accepted: 13 April 2024 – Published: 6 June 2024

Abstract. The severity and the extent of a large fire event that occurred on the small volcanic island of Stromboli (Aeolian archipelago, Italy) on 25–26 May 2022 were evaluated through remotely sensed data to assess the short-term effect of fire on local plant communities. For this purpose, the differenced normalized burned index (dNBR) was also used to quantify the extent of early-stage vegetation recovery dominated by *Saccharum biflorum* Forssk. (Poaceae), a rhizomatous C_4 perennial grass of Paleotropical origin. The burned area was estimated to have an extension of 337.83 ha, corresponding to 27.7 % of the island surface and to 49.8 % of Stromboli's vegetated area. On the one hand, this event considerably damaged the native plant communities, hosting many species of high biogeographic interest. On the other hand, *Saccharum biflorum* clearly benefited from fire. In fact, this species showed a very high vegetative performance after burning, being able to exert unchallenged dominance in the early stages of the postfire succession. Our results confirm the complex and probably synergic impact of different human disturbances (repeated fires and the introduction of invasive alien plants) on the natural ecosystems of small volcanic islands.

1 Introduction

Wildfires are a main disturbance factor affecting the Mediterranean terrestrial ecosystems, whose vegetation patterns are largely influenced by interactions with fire. Fire frequency and severity delineate landscape attributes (Pausas, 2006; Jouffroy-Bapicot et al., 2021), affect the structure and composition of the vegetation (Trabaud, 1994), and regulate speed and direction of ecological succession dynamics (Canelles et al., 2019). Also, fire causes sudden variations in the carbon and energy balance of ecosystems (Novara et al., 2013; Harris et al., 2016; Pausas and Millán, 2019) and in the soil microbial activity and functional diversity of the microbiome (Velasco et al., 2009; Goberna et al., 2012).

At the onset of human civilizations, Mediterranean landscapes were deeply modified by anthropogenic fires that were used to expand the open-canopy space available for human activities and facilitate a wide array of foraging activities (Pausas and Keeley, 2009). Throughout human history, demographic fluctuations, innovations, and cultural exchanges have always been accompanied by changes in land use and,

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thus, in fire regimes and the amount and patchiness of fuel (Guyette et al., 2002; Driscoll et al., 2021).

After the mid-twentieth century, land abandonment associated with an increase in woody cover and the buildup of fuels (Mantero et al., 2020) chiefly contributed to the increased fire hazard in the Mediterranean region (Le Houérou, 1993; Salis et al., 2022). Despite the occurrence of some natural factors favoring fires, most of them are ignited by humans through carelessness or voluntary action. Given that vegetation burning is strongly related to plant water content (Bond and Wilgen, 1996), fires happen mostly during the warmest and driest months, i.e., during the Mediterranean summer (Bergmeier et al., 2021). Climate change scenarios indicate rising temperatures and decreasing amounts of precipitation, resulting in longer summer aridity, soil water shortages, and increasing fire risk (Moriondo et al., 2006; Lozano et al., 2017; IPCC, 2021), despite the fact that lower productivity may limit fuel availability (Baudena et al., 2020).

Nevertheless, typical Mediterranean shrublands are highly resilient to relatively frequent, high-intensity fires, but changes in the fire regime may make these communities susceptible to compositional changes, potentially followed by alien plant invasions (Keely and Brennan, 2012; Vallejo et al., 2012). The positive feedback between invasive species and fire can be a major cause of unidirectional change in invaded ecosystems (Brooks et al., 2004), and invasive species able to sustain increased fire frequency and intensity may generate favorable conditions for their self-perpetuation (Pauchard et al., 2008).

Small islands are particularly vulnerable to biological invasions (Bellard et al., 2016) due to the combined effects of the reduced species pool and the competitive traits of invasive species. This process has been reported for Mediterranean islands (Celesti-Grapow et al., 2016; Fois et al., 2020), particularly in the case of volcanic islands with ongoing or recent volcanic activity (Karadimou et al., 2015; Pasta et al., 2017).

The island of Stromboli (northeast Sicily) represents an ideal case study for interactions between fires and invasive species because it has the lowest number of species, as expected within the archipelago species–area relationship among the seven largest islands of the Aeolian archipelago (Chiarucci et al., 2021).

This study uses remotely sensed data to analyze the post-fire damage to local vegetation through the application of a spectrally sensitive index, i.e., the differenced normalized burned index (dNBR), which has also been used to quantify the extent of the subsequent early-stage vegetation recovery, dominated by *Saccharum biflorum*, in order to highlight the ecological behavior of this invasive alien species and its fire-driven ability to colonize new spaces.

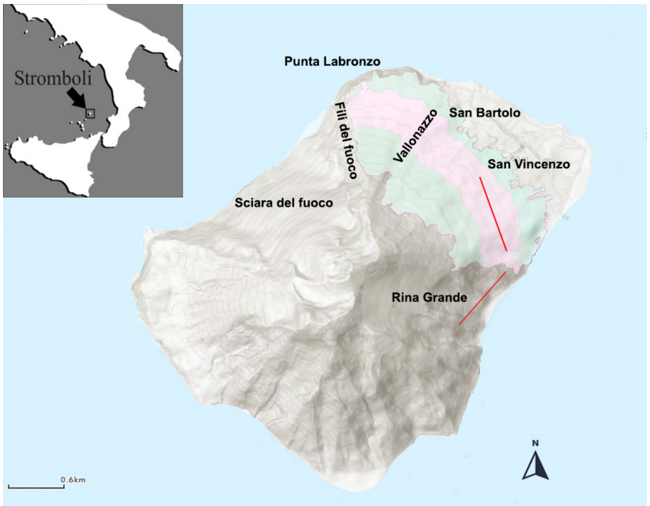

Figure 1. Map of the study area (light green) with the place names mentioned in the text. The pink color indicates the area where the vegetation plots for validation were sampled. The red lines identify the two transects along which the stem density of *Saccharum* was measured.

2 Material and methods

2.1 Study area

The island of Stromboli, 12.6 km^2, represents the northeastern end of the Aeolian archipelago, in the southeastern Tyrrhenian Sea, which is in the Mediterranean biogeographical region (Cervellini et al., 2020). Stromboli is the summit of the youngest and most active of the Aeolian islands; its subaerial activity began around 85 ka (Francalanci et al., 2013), and the emerged part consists of a single cone that rises up to 926 m above sea level (m a.s.l.). The island has quite a regular slope averaging 28° and two large horseshoe-shaped flank collapses named “Sciara del Fuoco” on the northwestern flank and “Rina Grande” on the southeastern flank. Our study area covers a surface of ca 3.4 km^2, between 50 and 530 m a.s.l., on the northern and eastern sides of Stromboli and can be roughly divided into two sectors. The northern sector is bounded by the “Fili del Fuoco” ridge, which overlooks Sciara del Fuoco, to the west and by the Vallonazzo valley to the east; the eastern sector is bounded by the Vallonazzo valley to the northwest and by the Rina Grande depression to the southeast (Fig. 1). Both sectors are characterized by medium to gentle slopes, with 80 % of the area sloping less than 30° (Fornaciai et al., 2010).

The climate of Stromboli is typically Mediterranean. At 4 m a.s.l., the average yearly temperature is 18.2 °C, with a mean temperature of 12.3 °C in the coldest month (January) and 26.0 °C in the warmest month (August). The annual rainfall averages 570 mm, while the relative humidity is 75.0 % in winter and 60.8 % in summer. Based on the WorldClim interpolated maps (Hijmans et al., 2005) and on the Rivas-

Martínez bioclimates classification (2004), the study area is characterized by an upper thermo-Mediterranean thermotype and a dry to sub-humid ombrotype (Bazan et al., 2015).

The study area was dominated by a typical Mediterranean rockrose garrigue (*Cistus creticus* subsp. *eriocephalus*; *C. monspeliensis*; and *C. salviifolius*) with scattered patches of maquis including *Genista tyrrhena*, *Spartium junceum*, *Olea europaea*, *Erica arborea*, and *Pistacia lentiscus* (Richter, 1984; Cavallaro et al., 2009). The former cultivated land and the volcanic ash deposits were colonized by *Saccharum biflorum*, while small *Quercus ilex* stands were occasionally found along the impluvium lines. Equally rare and scattered were the patches dominated by *Euphorbia dendroides*, limited to the rocky outcrops, especially along the south-facing rim of Vallonazzo valley (Ferro and Furnari, 1968; Richter and Lingenhöhl, 2002). The highest and southernmost end of the study area included part of the local population of *Cytisus aeolicus*, a narrow-ranging endemic broom growing only on the islands of Vulcano, Alicudi, and Stromboli (Zaia et al., 2020).

On 25–26 May 2022, due to recklessness during the filming of a television drama, a fire broke out in the upper outskirts of the village of San Vincenzo and, fuelled by a strong Sirocco wind, burned the whole of our study area. While *Saccharum* stands were entirely burned, very few small patches of garrigue and *Quercus ilex* stands escaped the fire.

2.2 Target species

By far the most common invasive alien species on Stromboli is *Saccharum biflorum* Forssk. (=*S. spontaneum* L. subsp. *aegyptiacum* (Willd.) Hack.; henceforth: *Saccharum*), a vigorously growing rhizomatous grass of Palaeotropical origin (Amalra and Balasundaram, 2006) with culms of 1.5–2.5 m and flowering stems up to 3 m high. Its rhizomes can be up to 6 m long, with nodes every 10–15 cm from which the culms and fascicled roots branch off (Sect. S1, Fig. S1 in the Supplement). This species has a C_4 metabolism and thrives in sandy and silty, often alluvial, soils (Pignatti et al., 2017–2019).

As for the Aeolian archipelago, *Saccharum* was introduced in the nineteenth century as a windbreak. Gussone (1832) recorded its occurrence (despite wrongly identifying it as *Saccharum ravennae* L.) on the islands of Stromboli, Panarea, Lipari, and Vulcano as "cultivated hedges in vineyards". *Saccharum* then spread on former cultivations and in abandoned terraced fields and wherever there was an accumulation of volcanic ash, as noticed by Ferro and Furnari (1968; our translation):

> a large part of the northeastern slope of the island, the very slope that Lojacono (1878) travelled through 'vineyards that produce beautiful wines', is covered by dense, almost-monophytic *Saccharum* vegetation, from sea level up to the upper limit of the ancient crops (...). This slope could have been colonized in a different way by native floristic elements, but it is difficult to make predictions on the final outcome of the competition, given the compactness of the *Saccharum* rhizomatous apparatus.

However, photos published by Ferro and Furnari (1968) give the impression that *Saccharum* from 50 years ago was more widespread than nowadays. Besides cultivation abandonment, the establishment of this plant is favored by fire, as observed by Richter (1984). Local elder people recall a major spread of *Saccharum* soon after the fire, which was caused by the intense eruption in 1930 and the subsequent abandonment of a large portion of the cultivated terraces along the eastern slopes of the island (Richter and Lingenhöhl, 2002). Another large fire event, ignited at the Punta Labronzo landfill site in 1978, promoted the recovery of *Saccharum* all over the eastern slopes above Punta Labronzo. In following years, the spread of this species was somewhat reduced by the development of native shrubland and garrigue, which, until recently, were the most widespread vegetation types in the study area.

2.3 Satellite imagery processing

To infer the extent of fire damage to the vegetation and the postfire surface of the resprouted *Saccharum* patches, we used optical satellite images acquired by the spaceborne Sentinel-2 sensor, which is a multispectral mission launched in the framework of the European Space Agency (ESA) Copernicus program (Drusch et al., 2012).

Sentinel-2 globally measures the backscattered solar radiation from ground targets with a temporal resolution of around 5 d across 13 spectral bands with different ground sampling distances (GSDs) varying from 10 to 60 m. In this work, we employed the four bands at a 10 m GSD, namely in the visible range (blue, green, and red) and near-infrared (NIR) range. We relied on band 12 in the shortwave infrared (SWIR) at a 20 m GSD to detect burned areas. Additionally, spectral bands 5, 6, 7, 8a, and 11, all at a 20 m GSD, were used for the supervised classification of different vegetation types. All other bands at a 60 m GSD were not used in this analysis. The products used were at processing level 2A, which provides date that are radiometrically corrected, georeferenced, orthorectified, atmospherically corrected, and converted to the bottom-of-atmosphere reflectance. The choice of using reflectance rather than radiance products is motivated by the following reasons: (1) the overall brightness differences in different images due to different acquisition conditions are reduced in the level 2A products, and (2) the quantities estimated from single images through spectral indices are more meaningful when applied to data in reflectance.

The data selection and processing were carried out on Google Earth Engine (GEE; Amani et al., 2020), which is at the same time a multi-petabyte repository of georeferenced and harmonized Earth observation raster, vector, and tabular datasets, which include the whole Sentinel-2 archive.

To quantify the damage caused by the abovementioned fire event to the vegetation, different Sentinel-2 scenes acquired in a relatively short time span were aggregated. An image composite of the island before the event was derived by considering eight acquisition dates with cloud cover below 5 % acquired before the fire event from 15 April to 22 May 2022 and considering the median reflectance for each image element. This allows the removal of abnormal values due to specific atmospheric conditions inducing errors into the reflectance estimation process, undetected clouds, and cloud shadows in the scene. The postfire reflectance was estimated by applying the same processing to six acquisition dates after the event, from 26 May to 15 June 2022. The two image composites are reported in Fig. 2. Therein, pre- and post-event true-color images obtained from Sentinel-2 bands in the visible range (namely bands 4, 3, and 2) can be visually assessed, with damage caused by the fire in the northeastern part of the island already evident in this band combination.

In order to estimate vegetation loss and total burned area, we derived the normalized burn ratio (NBR), defined for a multispectral image x, as

$$\mathrm{NBR}(x) = \frac{\mathrm{NIR} - \mathrm{SWIR}}{\mathrm{NIR} + \mathrm{SWIR}},$$

where NIR and SWIR indicate reflectance in the near-infrared and shortwave infrared, represented for Sentinel-2 by bands 8 and 12, respectively. The NBR is a commonly used index to detect burned area and burn severity (Key and Benson, 2006) and is particularly sensitive to the changes in the amount of live green vegetation, moisture content, and some soil conditions, which may occur after a fire (Lentile et al., 2006).

Change detection relying on spectral indices from multitemporal pre-fire and postfire images can be used to estimate vegetation loss or recovery. Relying on the availability of multitemporal images, we used the differenced NBR(dNBR) since it performs well in capturing the spatial severity within fire perimeters (Picotte and Robertson, 2010; Soverel et al., 2010).

The dNBR related to pre- and post-event images, respectively x_{t_0} acquired at time t and x_{t_1} acquired at time t_1, is the delta of the two measurements:

$$\mathrm{dNBR}(x_{t_0}, x_{t_1}) = \mathrm{NBR}(x_{t_0}) - \mathrm{NBR}(x_{t_1}).$$

This equation has been used to estimate both fire severity and vegetation recovery after the fire event: a negative dNBR is correlated with recovery after fires, while a positive one indicates damage, with the severity proportional to the dNBR value.

We first estimated the area affected by fire immediately after the event by computing the dNBR for the whole island. The affected area was derived by applying the damage classes defined in Key and Benson (2006). In particular, the value of the dNBR in the middle of the range related to low-severity damage (0.0-0.27) and approximated to the second decimal place, specifically 0.19, was selected and assessed using expert knowledge in order to exclude false positives from the estimation and perform further analysis only on relevant image elements, considering as damaged all image elements with the dNBR above this threshold (Fig. 2). This was necessary as using the value of 0.1 was raising false alarms, most notably within urban areas.

To check whether the severity of the damage was related to geomorphological features, rather than to different vegetation units, the correlation between results of the dNBR and a digital elevation model (DEM) was evaluated. The normalized difference vegetation index (NDVI; Gandhi et al., 2015) was also applied in order to estimate the loss in live green vegetation, and its correlation with dNBR values was checked (Sect. S2).

Finally, in order to evaluate the quality of our results, we computed a new dNBR between the pre-event image and a mosaic of Sentinel-2 acquisitions from the time range of 15–17 August 2022. The burned area detected in such a way was compared with high-resolution images acquired by a drone professional flying a *DJI Phantom 3* drone on 17 August 2022, i.e., around 3 months after the fire event and 5 d after the first intense rainstorm. Drone images were merged and georeferenced through the software Agisoft Photoscan Professional (version 1.2.6). These images have a 10 cm GSD and were mosaicked over the northeastern part of the island, covering the inhabited area of San Bartolo and San Vincenzo. The drone images did not cover the higher elevations of our study area, closer to the volcano's vents, or the northernmost part, near Punta Labronzo (Fig. 4).

2.4 Vegetation recovery assessment

The mentioned image composite of Stromboli, derived from eight acquisitions from April–May 2022, was also used to map the structural types of the vegetation affected by the fire through supervised classification based on spectral information. Three vegetation classes have been defined: maquis, garrigue, and Saccharum. The "maquis" class groups tall woody vegetation patches, namely (1) shrublands including *Genista tyrrhena*, *Spartium junceum*, *Erica arborea*, and *Pistacia lentiscus*; (2) abandoned olive groves invaded by *Cytisus infestus* and *C. laniger*; (3) *Quercus ilex* groves; (4) *Euphorbia dendroides* shrublands; and (5) *Cytisus aeolicus* shrublands. The "garrigue" class refers to vegetation patches with dwarf shrubs, subshrubs, and bunchgrasses, including (1) dwarf shrublands dominated by *Cistus sp. pl.*; (2) herbaceous–chamaephytic vegetation dominated by *Cymbopogon hirtus*, *Oloptum miliaceum*, *Centranthus ruber*, *Jacobaea maritima* subsp. *bicolor*, and *Scrophularia canina*; and (3) small impluvia colonized by *Rubus ulmifolius* and *Pteridium aquilinum*. Finally, the vegetation patches dom-

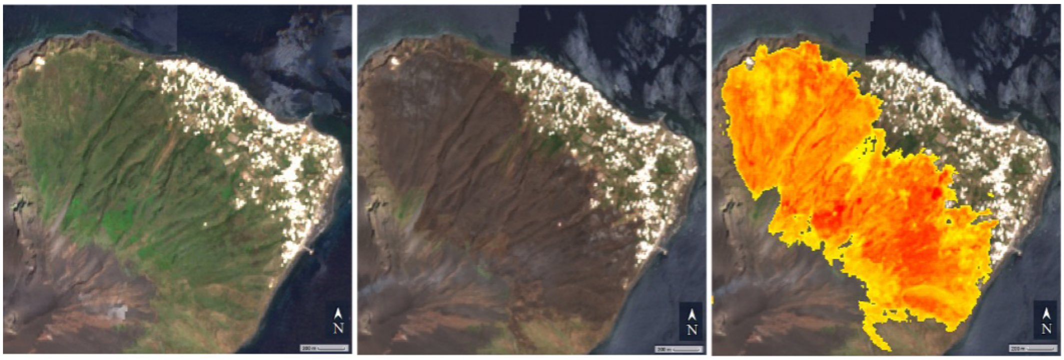

Figure 2. From left to right: Sentinel-2 image before the fire event (composite of acquisitions in the time period of 22 April–22 May 2022); Sentinel-2 image after the fire event (composite of acquisitions in the time period of 25 May–15 June 2022); dNBR-inferred burned area (yellow: low-severity damage, orange: middle-severity damage, and red: high-severity damage) overlaid on the middle image composite.

inated by *Saccharum* were attributed to the "Saccharum" class, easily recognized by its typical yellowish-green color and remarkable structural homogeneity, given by one single species covering well over 80 % of the soil. These patches have two different textures: a smoother texture where *Saccharum* has invaded abandoned vineyards and a more granular texture where *Saccharum* has invaded former fig tree plantations, as happened in the upper part of our study area.

For each of the three classes described above, 10 patches of 50 pixels each were selected by experts to constitute the training dataset, and 150 random points equally split among the three classes constituted the validation dataset. The area where damage occurred was fed to a support vector machine (SVM) classifier (Hearst et al., 1998), as implemented in the *libsvm* routine in GEE using a linear kernel and setting the cost C to 1. The input parameters were all Sentinel-2 spectral bands, namely 2 to 8, 8a, 11, and 12, that had a ground sampling distance of 10 or 20 m. The results of the classification algorithm (Fig. 3) were evaluated through visual analysis by experts and numerically validated using the validation dataset, yielding an overall accuracy higher than 90 %.

To check variations in the distribution of burn severity levels, and to evaluate the short-term response after a fire among different vegetation types, the pixel values of the dNBR were randomly sampled at 50 random points for each of the three vegetation classes described above. Levene's test was used to assess the homogeneity of variance followed by the nonparametric Kruskal–Wallis test, using chi-square distribution (right-tailed) and Dunn's post hoc comparison to reject the null hypothesis.

To evaluate the short-term vegetation response after a fire, the composite images of Sentinel-2 acquisitions from the following time ranges were analyzed: 15–17 August 2022, 14–26 September 2022, 22–28 October 2022, and 10 May–15 June 2023.

On-site surveys were carried out on 15–19 September 2022, 7–9 March 2023, and 9–12 September 2023 in order to validate the remotely sensed data and to sample vege-

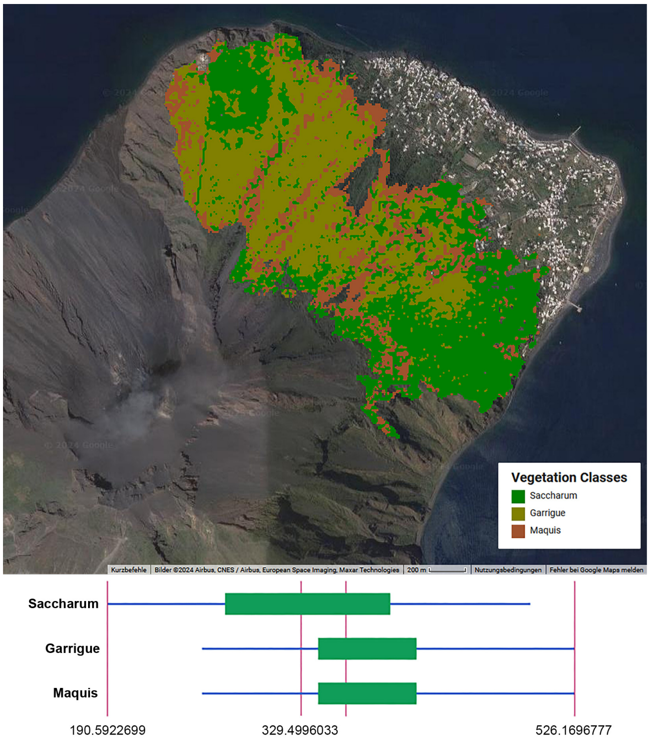

Figure 3. The top panel shows a supervised classification of vegetation classes in the study area, overlaid on a Google Earth base map (© Google Earth 2024, CNES/Airbus, European Space Imaging, Maxar Technologies). The bottom panel shows a box plot showing the distribution of dNBR values per vegetation class, evaluated on the image composites from acquisitions in the periods of 15 April–22 May and 26 May–15 June 2022. Boxes and whiskers correspond to 1 and 2 standard deviations, accounting for 68 % and 95 % of the processed values, respectively. The fire that occurred in garrigue and maquis was estimated to be the most severe.

tation plots in the burned area. The vegetation was sampled in 38 plots, 10 m^2 each, and randomly selected along a belt between 180 and 220 m a.s.l. (Fig. 1). To optimize the sampling effort, the location of the sampling sites deviated little from the paths that run along the volcano's flank above the villages of San Vincenzo and San Bartolo. The only rules adopted were that the plots should have been at least 50 m apart in order to avoid spatial autocorrelation and that each of the abovementioned three vegetation classes should have been represented by at least 10 plots. Vegetation data were collected using a modified Braun-Blanquet (1964) approach by visually estimating the cover–abundance in percentage values and by measuring the mean and maximum height (in cm) of each species.

In order to collect useful information to better understand the interaction between *Saccharum* and fire, a comparative evaluation of stem density per square meter in burned vs. unburned patches was carried out in the field on 18 September 2022. Sampling plots 1×1 m were located every 100 m along two almost-contiguous transects, which were 900 m long, 10 inside the burned area, above the village of San Vincenzo, and 10 outside the burned area, in the bottom part of Rina Grande (Fig. 1). In each plot, the number of stems of *Saccharum* was counted and the average and maximum height was recorded. In the unburned patches, the relative percentage of dry stems compared to green stems was also assessed in order to showcase the ease of fire ignition due to the abundant presence of dry biomass, consisting mainly of the flowering stems of *Saccharum* which, once faded, dry out completely but remain standing as they are supported by the green stems which have not yet flowered.

3 Results

The application of the dNBR yielded a severity map showing the difference between pre-fire and postfire acquisitions. The burned area was quantified in 337.83 ha, corresponding to 27.7 % of the island surface (Fig. 2). Concerning the burn severity (Keeley, 2009), 75.15 ha showed a low severity level, 218.37 ha showed an intermediate severity level, and 44.31 ha showed a high severity level. The Kruskal–Wallis H test indicated a significant difference in the distribution of severity levels among vegetation classes ($\chi^2(2) = 8.56$, $p = 0.013$), where the burned garrigue and maquis suffered higher-severity damage than *Saccharum* (Fig. 3).

We found no correlation between the dNBR and neither the elevation nor the slope (therefore not reported here). NDVI values were strongly correlated with dNBR values (Pearson correlation of 0.97; see Sect. S2). However, NDVI showed some noise in the estimation of vegetation loss and false positives scattered across the inhabited area. Therefore, these results are not reported further in this paper, despite the NDVI having a true resolution of 10 m in Sentinel-2 products, while NBR employs the SWIR band, which is originally at a 20 m GSD and therefore interpolated.

Considering the limitations imposed on spatial resolution by the satellite-derived damage evaluation, the burned area detected by the dNBR from the mosaic of Sentinel-2 acquisitions in the time range of 15–17 August 2022 well matched the burned area observable in the drone image acquired on 17 August, with humanmade structures and even single trees that were spared by the fire correctly regarded as undamaged in the dNBR estimation (Fig. 4). At the same time, partially burned vegetated areas were correctly included in dNBR results because even if they did not burn completely, a steep decrease in the red edge portion of the spectrum around 700 nm revealed strong vegetative stress.

The NDVI calculated with a threshold of 0.08, therefore quantifying all pixels having at least 8 % covered by photosynthetically active vegetation, quantified the area of the island covered by vegetation before the fire as 678.73 ha. Considering the described correlation between the dNBR and NDVI, and the area affected by the fire as computed by the dNBR, it can be concluded that roughly half (49.8 %) of the vegetated area of Stromboli was burned during the fire event.

Figure 5 shows the vegetation recovery in the area affected by the fire. According to the thresholds suggested by Key and Benson (2006) to categorize recovery levels from dNBR values, in the specific enhanced low and high regrowth for dNBR values ranging from -100 to -250 and smaller than -250, respectively, 1 year after the fire, 53.25 % of the burned area showed a high enhanced recovery, 30.84 % showed a low recovery, and 15.9 % showed no recovery. Among the three vegetation classes considered, 56.08 % of the pixels with high recovery levels were *Saccharum*, 38.2 % were garrigue, and 5.7 % were maquis. Conversely, 10.46 % of the areas with no recovery were maquis, 65.48 % were garrigue, and 23.86 % were *Saccharum*. Considering the distribution of recovery levels across the first growing season after the fire, *Saccharum* is clearly characterized by a faster recovery with respect to the maquis and the garrigue, particularly at the beginning of the first growing season after the fire (September–October 2022).

Referring to the vegetation recovery estimated in October 2022, the Kruskal–Wallis H test indicated that there is a significant difference among the vegetation classes ($\chi^2(2) = 8.41$, $p = 0.015$) with a mean rank score of 64.06 for *Saccharum*, 89 for garrigue, and 73.44 for maquis. The post hoc Dunn's test using a Bonferroni-corrected alpha of 0.017 indicated significant differences of *Saccharum* recovery towards both maquis and garrigue (Table 1).

The results of the spectral evaluation of the vegetation recovery are confirmed by the on-site surveys. Table 2 shows the median values of percentage cover and height of resprouts and seedlings in the plots sampled in September 2022 and March and September 2023. The distribution of the plots across the vegetation classes was the following: 10 *Saccharum*, 16 garrigue, and 12 maquis. The Kruskal–Wallis H test

Figure 4. The left panel shows a high-resolution drone image, overlaid on a high-resolution image from a Google Earth base map, acquired on 17 August 2022 to assess the quality of the information derived from the dNBR analysis. The top-right panel shows pre-fire detail from a Google Earth base map. The middle-right panel shows postfire detail from a drone image. The bottom-right panel shows the same detail with overlaid thresholded dNBR values higher than 0.19 (using pre-fire and the August 2022 scene), and it is semitransparent for visual comparison (yellow: low-severity damage, orange: middle-severity damage, and red: high-severity damage). Credits of the drone images: Antonio Zimbone. Credits for Google base map: © Google Earth 2024, CNES/Airbus, European Space Imaging, Maxar Technologies.

Table 1. Dunn's post hoc comparison for the dNBR-estimated recovery of the considered vegetation classes in the burned area on October 2022.

Pair	Mean rank difference	Z	SE	p value	p value/2
Saccharum–maquis	−24.94	2.8703	8.6891	0.004101	0.002051
Saccharum–garrigue	15.56	1.7908	8.6891	0.07333	0.03667
Garrigue–maquis	−9.38	1.0795	8.6891	0.2804	0.1402

indicated highly significant differences ($p < 0.001$) between the cover values and height of resprouts and the cover of seedlings in the *Saccharum* plots compared to those ascribed to the other two vegetation classes. No significant difference was found in the height of the seedlings or even in the composition of the species across the vegetation classes (data not shown), which in all cases were largely dominated by annual plants such as *Brassica fruticulosa*, *Ornithopus compressus*, *Lupinus angustifolius*, *Trifolium stellatum*, and seedlings of *Cistus* sp. pl. (mainly *Cistus creticus*).

The estimated vegetation composition in the study area shows that already in August, resprouting *Saccharum* had invaded approximately 13 % of areas previously occupied by other vegetation classes, especially along gullies. This latter percentage remained almost unchanged in the following months (Fig. 6). The fast recovery of the *Saccharum* patches, with their soft-green color standing out against the surrounding black, became evident as early as a few weeks after the fire (Sect. S1, Figs. S3–S5). Until the first rains, which occurred on the night of 12 August 2022, *Saccharum* was the only green spot in the fire-affected areas, and the high-resolution drone images captured on 17 August 2022 clearly show all *Saccharum* patches in their recovery phase (Fig. 4). In the Sentinel-2 images from September–October 2022, previous damage from the fire event appears to be mitigated. In more detail, a total of 110 ha of the previously burned area (roughly one-third) exhibit a dNBR value below −0.1, which represents a strong indicator of vegetation recovery. This was mostly due to *Saccharum*, demonstrating that this species can exert unchallenged dominance in the early stages of the post-fire dynamics (succession), reaching vegetative stem densities only slightly lower than those of the unburned stands in a short time (Fig. 7).

4 Discussion

Our study confirms that fire severity can be mapped with high accuracy using indices derived from Sentinel-2 imagery with supervised vegetation classifications based on spectral information (Gibson et al., 2020). Fire has been a major driving force for Mediterranean insular ecosystem dynamics since the emergence of the Mediterranean climate (Médail,

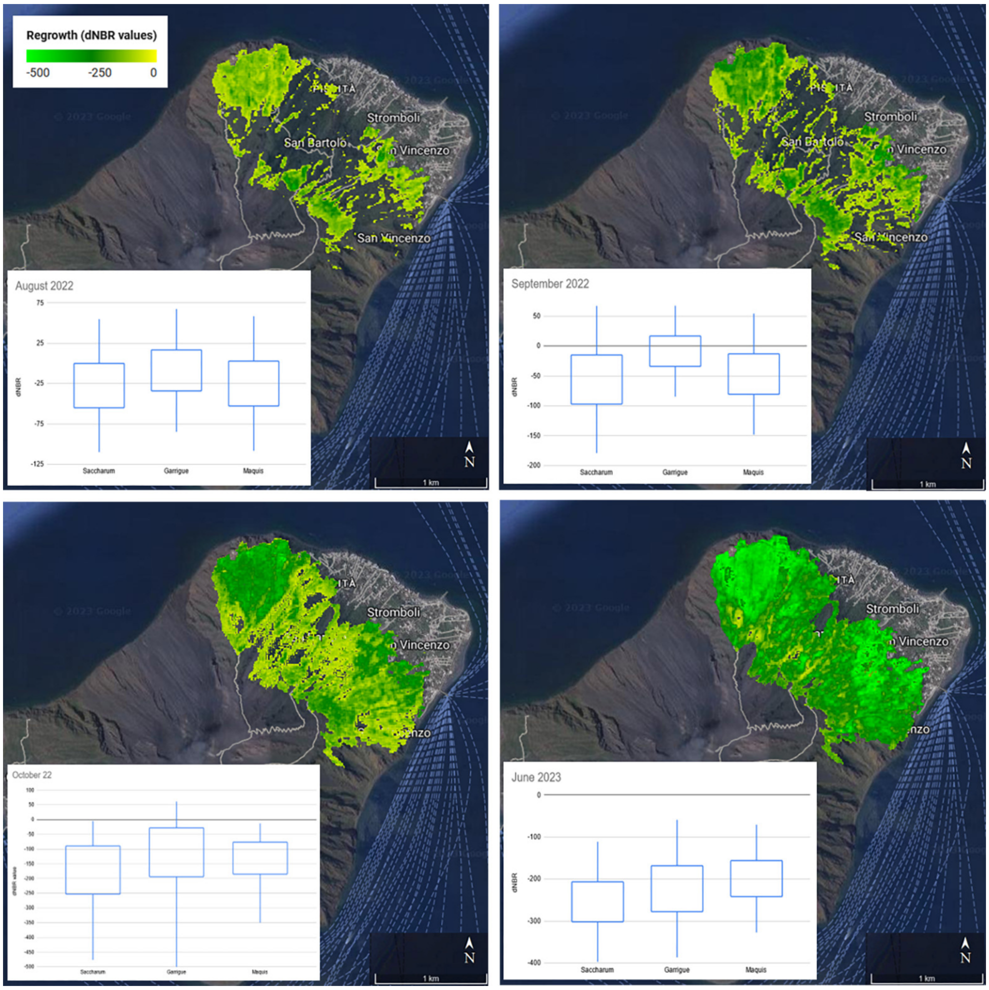

Figure 5. Vegetation recovery in the area affected by the fire, estimated through dNBR values from different acquisitions of Sentinel-2 images, overlaid on a Google Earth base map (© Google Earth 2024, CNES/Airbus, European Space Imaging, Maxar Technologies). Box plots show the distribution of dNBR values associated with recovery in the areas occupied by Saccharum, garrigue, and maquis. Boxes and whiskers correspond to 1 and 2 standard deviations, accounting for 68 % and 95 % of the processed values, respectively. The following thresholds were suggested by Key and Benson (2006) to categorize levels of recovery from dNBR values rescaled by 1000: no change from 0 to −100, low enhanced recovery from −100 to −250, and high enhanced recovery (high) from −250. Saccharum is characterized by faster recovery than the maquis and the garrigue, particularly at the beginning of the first growing season after the fire (September–October 2022).

Table 2. Median values of cover (%) and height (cm) of resprouts and seedlings in the validation plots. Values in parentheses indicate positive absolute deviations from the median values.

Date	Vegetation	Resprout cover	Resprout height	Seedling cover	Seedling height
15–19 September 2022	Saccharum	85 (5)	150 (20)	5 (0)	9 (13)
	Garrigue	10 (15)	8 (17)	25 (25)	13 (21)
	Maquis	15 (15)	15 (12)	30 (30)	14 (16)
7–9 March 2023	Saccharum	90 (0)	160 (20)	10 (5)	43 (14)
	Garrigue	20 (10)	23 (24)	40 (20)	33 (22)
	Maquis	20 (15)	27 (38)	50 (25)	38 (25)
9–12 September 2023	Saccharum	90 (0)	160 (20)	10 (10)	53 (19)
	Garrigue	25 (15)	20 (32)	55 (15)	47 (32)
	Maquis	25 (30)	36 (47)	50 (20)	55 (30)

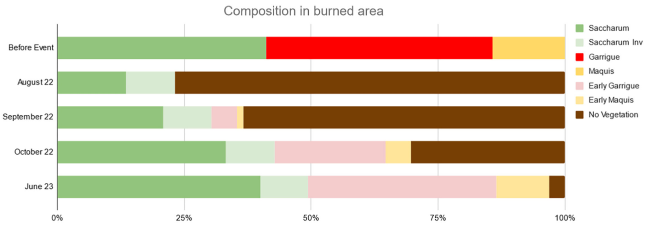

Figure 6. Estimated vegetation composition in the study area (cover %). “Saccharum” vegetation patches occupied by *Saccharum* both before and after fire; “Saccharum Inv” sums the surface areas previously occupied by other vegetation units and invaded by Saccharum after fire. “Early garrigue” and “Early maquis” refer to early post-fire successional stages of these two vegetation classes, dominated by annual plants and resprouted shrubs and seedlings of perennial seeders, chiefly *Cistus sp. pl.*

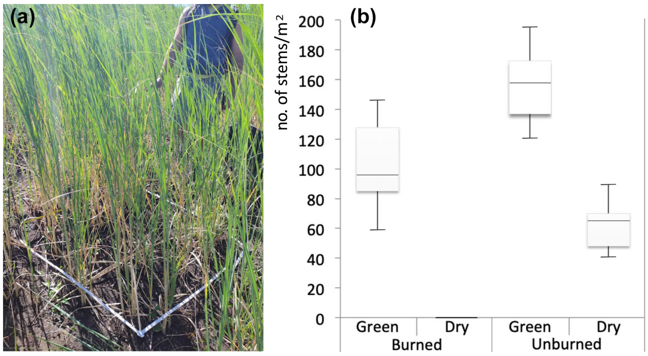

Figure 7. (a) Measuring resprouted *Saccharum biflorum* stem density in one of the plots within the burned area (18 September 2022; photo by Riccardo Guarino). **(b)** Box plots of the stem density of *Saccharum* in burned and unburned patches.

2021), particularly in volcanic island ecosystems (Irl et al., 2014). This paper provides the first report of how a single fire event significantly affected Stromboli island, burning 50 % of the vegetated island surface. This clearly influenced the island biota, particularly the native vegetation, which is rich in species of relevant biogeographic interest, such as *Centaurea aeolica*, *Genista tyrrhena*, *Dianthus rupicola* subsp. *aeolicus*, and *Jacobaea maritima* subsp. *bicolor* (Pasta et al., 2024). In addition, the highest and southernmost end of the study area included part of the *Cytisus aeolicus* population, one of the rarest and most emblematic endemic plant species of the Aeolian archipelago (Zaia et al., 2020).

Although we applied a permissive threshold (8 %) in the NDVI for our quantitative analysis, our conclusion that the fire that occurred on 25–26 May 2022 burned roughly half of Stromboli’s vegetated area appears reasonably accurate when considering all the available data we used for validation. Our study confirms that burn severity levels, estimated by the dNBR, are higher in woody vegetation (Koutsias and Karteris, 2002), presumably due to the larger aboveground biomass and dead organic matter stock in the case of maquis (Rossetti et al., 2022) and to the high flammability of Mediterranean dwarf shrubs in the case of garrigue (Dimitrakopoulos, 2001). Despite the garrigue being mostly formed by pyrophytes and obligate seeders, and despite it being among the first shrubs to emerge after a fire (Palá-Paúl, 2005; Athanasiou et al., 2023), our study demonstrated that *Saccharum* exhibits even greater resilience compared to garrigue in the earliest stages after a fire, with a clear risk of altering the recovery patterns of native vegetation, which, especially on volcanic islands, is characterized by a high abundance of nitrogen fixers and annual species (Weiser et al., 2021).

The positive interaction between *Saccharum* and fire was already noticed in Stromboli by Richter (1984) and Richter and Lingenhöhl (2002). Fire spreads very easily across *Saccharum* vegetation due to the abundant presence of standing dry biomass (Sect. S1, Figs. S2, S4, S6). This result agrees with many recent studies focused on the role of fire as a promoter of C_4 grasses (Scheiter et al., 2012; Hoetzel et al., 2013; Ripley et al., 2015). Although the native rockrose garrigue vegetation is also adapted to, and favored by, periodical fires (Pausas, 1999), its survival derives from the ability of *Cistus* to develop a long-lasting soil seed bank (Roy and Sonie, 1992; Scuderi et al., 2010). Too frequent fire events and runoff caused by heavy rainfall on sandy and incoherent soils may cause a critical depletion of the soil seed bank and favor sprouters against obligate seeders. For this purpose, we must point out that the autochthonous sprouters (such as *Erica arborea*, *Pistacia lentiscus*, and *Olea europaea*) have a slower growth rate than *Saccharum* and need a longer time to become established.

After the fire, our study area was exposed to full solar radiation; dark sandy surfaces were subject to extreme microclimatic (surface temperatures up to 80 °C; see Richter, 1984) and dry conditions. These were not favorable for the germination of the soil seed bank since sprouters faced almost no competition until the first rains, which occurred on 12 August 2022. The first and most important beneficiary of these contrasting conditions was *Saccharum*, which, over time, was able to colonize large surfaces of tephra in the northern and eastern parts of the island, likely due to a positive interaction between land abandonment, repeated fires, and volcanic ash deposition. *Saccharum* is extremely competitive thanks to a variety of functional strategies (e.g., C_4 photosynthetic pathway, large resource allocation into clonal and bud-bearing rhizomes which ensures a quick resprouting, space occupancy, and resource uptake) under current and probably also under predicted conditions (likely more disturbed), which could affect and define different ecosystems on Stromboli.

According to Lojacono (1878), *Saccharum* was planted along the vineyards to shelter them from the northerly winds (Fig. 8). This condition lasted until the eruption on 11 September 1930, which is considered, so far, to be the most violent and destructive event in the historical records

Figure 8. The left panel shows a historical photo of terraced vineyards on Stromboli (1891; anonymous photographer) with rows of *Saccharum biflorum* used as windbreaks. The right panel shows the same view 130 years later (16 July 2021; photo by Pietro Lo Cascio).

of Stromboli's activity (Rittmann, 1931). Facilitated by the winter rains and by a rapid expansion via rhizomes, *Saccharum* first benefited from the emigration of most inhabitants and subsequent abandonment of terraced fields, which, in a very short time lapse, were almost completely sealed off by a dense monospecific bed; this made it difficult for other species to establish themselves (Ferro and Furnari, 1968; Richter, 1984). Since then, competition for space between local native vegetation and *Saccharum* beds has been regulated mainly by the periodical occurrence of fires. Further studies are needed to understand the duration of the *Saccharum* expansion phases. Our preliminary results suggest that the expansion of *Saccharum* is surprisingly fast, but the decline may also be relatively rapid. There are no data on the longevity of *Saccharum* rhizomes and related senescence processes or on the effects of volcanic ash deposition on rhizome burial. However, there are reasonable indications that, if the vegetation is not too frequently affected by fire, *Saccharum* could be gradually replaced by native vegetation within a few decades, as captured in the maps published as "Fig. 4" by Richter and Lingenhöhl (2002).

On 12 August 2022, a severe thunderstorm triggered disastrous erosion processes over the entire area affected by the fire on 25–26 May. Large quantities of mud, stones, and volcanic ash flooded the streets in the villages of San Bartolo and San Vincenzo (Sect. S1, Fig. S7). In the burned area, the traces of runoff and surface rill erosion were still very evident during our inspections on 18–19 September 2022. However, just as evident was the ambivalent role of *Saccharum*, which, on the one hand, clearly prevails over native species and, on the other hand, thanks to its dense mat of rhizomes, proves to be much more efficient than the burned native vegetation in counteracting hydrogeological instability. The latter is a very relevant aspect on a volcanic island where the soils are largely made up of loose tephra ashes.

Over time, *Saccharum* beds have become an important secondary habitat for many animal species. In fact, they represent the main breeding site for at least 70 % of breeding bird species on Stromboli (Massa et al., 2015) and host conspicuous populations of almost all terrestrial vertebrates occurring on the island (especially *Tarentola mauritanica*, *Podarcis siculus*, and *Hierophis viridiflavus*). Some of the invertebrates that are found in the *Saccharum* beds are of considerable biogeographic interest, such as *Caulostrophus zancleanus*, a regional endemic (Lo Cascio et al., 2022), and the recently described *Catomus aeolicus*, an endemic of the northeastern sector of the Aeolian archipelago (Ponel et al., 2020). Although not specialized on *Saccharum*, the rhizophagous larvae of the melolonthid *Anoxia orientalis*, a species considered rare at the national scale in Italy, feed on its rhizomes. Surprisingly enough, *S. biflorum* does not seem to be an attractive fodder for the mammals introduced in historical (*Oryctolagus cuniculus*) or more recent (*Capra hircus*) times nor have significant infestations of phytophagous insects ever been observed. Thus, herbivory does not seem to be a limiting factor to the expansion of *Saccharum* on Stromboli.

5 Conclusions

Remotely sensed data provide fast, accurate, and reliable information for postfire damage analysis, being spectrally sensitive to vegetation features and structure. Multitemporal data acquisition allows observations on early-stage vegetation dynamics which, in our case, point out the outstanding pioneer role played by *Saccharum biflorum*, showcasing its ability to colonize and dominate large areas, potentially altering the recovery patterns of native vegetation. On the other hand, *Saccharum* proves to be efficient in stabilizing the soil, especially on a volcanic island with loose tephra ashes, thus mitigating the erosion processes. Our findings underscore the complex interplay between fire, vegetation dynamics, and ecosystem recovery on Stromboli, emphasizing the need for further research to better understand the long-term dynamics of *Saccharum* expansion, its interactions with native biota, and its potential use in environmental restoration. While considering the fragility of the context, considering that *Saccharum* is already widespread on the island, its rhizomes could be used to contain the disastrous effects of erosion caused by rainfall, later supporting the biological succession through the manual thinning of *Saccharum* culms and the sowing of the native woody species typical of local garrigue.

In fact, although the expansion of *Saccharum* proves to be surprisingly fast, its decline may also be relatively rapid as well if local vegetation is no longer affected by fire. After the abandonment of the agricultural practices in the highest portion of the island, the rewilding process could lead to the replacement of the large beds dominated by this invasive grass by native woody vegetation within a few decades.

Code availability. The code is available as a Google Earth Engine application (in the cloud) on demand by contacting the authors.

Data availability. The optical satellite data used in this study are open and available as Copernicus Sentinel-2 (ESA, 2021; https://doi.org/10.5270/S2_-znk9xsj). Furthermore, the data are accessible on the cloud through the Google Earth Engine environment (https://earthengine.google.com, Google Earth Enginge, 2024).

Supplement. The supplement related to this article is available online at: https://doi.org/10.5194/bg-21-2717-2024-supplement.

Author contributions. RG and DC developed the research idea, DC processed the satellite and drone imagery, RG and RZ conducted the fieldwork, RG led the writing process, and all authors discussed the results and contributed to the manuscript.

Competing interests. The contact author has declared that none of the authors has any competing interests.

Special issue statement. This article is part of the special issue "The role of fire in the Earth system: understanding interactions with the land, atmosphere, and society (ESD/ACP/BG/GMD/NHESS inter-journal SI)". It is a result of the EGU General Assembly 2020, 4–8 May 2020.

Acknowledgements. We would like to thank Giuseppe De Rosa, who brought Daniele Cerra and Riccardo Guarino together, and Antonio Zimbone for driving the drone flight and taking the pictures used to check the quality of the information derived from the dNBR analysis. Gianluigi Ottaviani and three anonymous reviewers are gratefully acknowledged for their suggestions on an earlier version of the manuscript.

Financial support. This research has been supported by the Ministero dell'Istruzione e del Merito (grant no. PRIN B53D23032530001).

Review statement. This paper was edited by Kirsten Thonicke and reviewed by three anonymous referees.

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