



MOSEV: a global burn severity database from MODIS (2000–2020)

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Received: 10 November 2020 – Discussion started: 19 November 2020

Revised: 9 March 2021 – Accepted: 28 March 2021 – Published: 8 May 2021

Abstract. To make advances in the fire discipline, as well as in the study of CO₂ emissions, it is of great interest to develop a global database with estimators of the degree of biomass consumed by fire, which is defined as burn severity. In this work we present the first global burn severity database (MOSEV database), which is based on Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance and burned area (BA) products from November 2000 to near real time. To build the database we combined Terra MOD09A1 and Aqua MYD09A1 surface reflectance products to obtain dense time series of the normalized burn ratio (NBR) spectral index, and we used the MCD64A1 product to identify BA and the date of burning. Then, we calculated for each burned pixel the difference of the NBR (dNBR) and its relativized version (RdNBR), as well as the post-burn NBR, which are the most commonly used burn severity spectral indices. The database also includes the pre-burn NBR used for calculations, the date of the pre- and post-burn NBR, and the date of burning. Moreover, in this work we have compared the burn severity metrics included in MOSEV (dNBR, RdNBR and post-burn NBR) with the same ones obtained from Landsat-8 scenes which have an original resolution of 30 m. We calculated the Pearson's correlation coefficients and the significance of the relationships using 13 pairs of Landsat scenes randomly distributed across the globe, with a total BA of 6904 km² ($n = 32\,163$). Results showed that MOSEV and Landsat-8 burn severity indices are highly correlated, particularly the post-burn NBR ($R = 0.88$; $P < 0.001$), and dNBR ($R = 0.74$; $P < 0.001$) showed stronger relationships than RdNBR ($R = 0.42$; $P < 0.001$). Differences between MOSEV and Landsat-8 indices are attributable to variability in reflectance values and to the different temporal resolution of both satellites (MODIS: 1–2 d; Landsat: 16 d). The database is structured according to the MODIS tiling system and is freely downloadable at <https://doi.org/10.5281/zenodo.4265209> (Alonso-González and Fernández-García, 2020).

1 Introduction

More than half of the land surface on Earth can be affected by fire, an area about the size of the European Union being burned annually (Keeley et al., 2011; Moritz et al., 2012; Andela et al., 2019). Thus, fire is a phenomenon of great interest because of its relevance worldwide but also because of expected changes in fire regimes as a consequence of global warming and land use change (Moreira et al., 2020). Among these changes, previous work has reported that fire weather seasons have recently increased (18.7 % from 1979 to 2013)

(Jolly et al., 2015), whereas burned area (BA) has decreased globally (24.3 % from 1996 to 2015) (Andela et al., 2017; Forkel et al., 2019) mainly because of the agricultural expansion in fire-dependent savannas (Andela et al., 2017).

The availability of satellite imagery with moderate spatial resolution (250–500 m) and daily or near-daily temporal resolution has enabled the production of several global BA products. Among the most accepted are those based on the Moderate Resolution Imaging Spectrometer (MODIS) (Chuvieco et al., 2016), which retrieves information of the en-

fire Earth in 36 spectral bands every 1 to 2 d. The MODIS MCD64A1 C6 product (Giglio et al., 2018) is the standard NASA BA product and probably the most used by the scientific community (Boschetti et al., 2019; Humber et al., 2018). The MCD64A1 BA product is calculated with surface reflectance time series and fire active masks (Giglio et al., 2018) and was recently validated with Landsat imagery across the globe (stage-3 validation), reaching coefficients of determination above 0.70 despite an underestimation of small fires as a consequence of its moderate spatial resolution (~ 500 m) (Boschetti et al., 2019). Global BA products are essential to know the patterns of fire occurrence, fire extent, fire propagation (Rodrigues and Febrer, 2018) and fire frequency (Andela et al., 2019). Thus, BA products may be useful to provide an estimation of the global carbon emissions from biomass consumption (Veraverbeke et al., 2015; van der Werf et al., 2017). However, to go one step further in determining fire impacts on ecosystems, as well as global carbon emissions, it is necessary to characterize burned areas according to the degree of biomass consumption (Keeley, 2009; van der Werf et al., 2017).

The term used to define the degree of biomass consumption and the overall impact caused by fire on ecosystems is fire severity (preferred for field measurements) or burn severity (preferred for remote sensing measurements) (Keeley, 2009). Traditionally, burn severity has been quantified from Landsat sensors through different methods, including those based on radiative transfer models (Chuvienco et al., 2006; De Santis et al., 2009), spectral unmixing (Quintano et al., 2017) and spectral indices (Chu and Guo, 2014; Fernández-García et al., 2018a). Among them, the standard method to quantify burn severity is through the delta normalized burn ratio (dNBR) (Key and Benson, 2006) spectral index and its relativized version (RdNBR) (Miller and Thode, 2007) which is less dependent on the pre-fire vegetation and potentially more suitable than dNBR for comparisons among zones with different environmental conditions (Miller and Thode, 2007; Rahman et al., 2018). Both spectral indices are based on the change caused by fire in near-infrared (NIR) and shortwave-infrared (SWIR) reflectance, which are highly sensitive to canopy density and moisture content respectively (Chuvienco, 2010). The dNBR and RdNBR indices calculated from Landsat have shown a high capacity (R^2 about 0.75) to correlate field measurements of biomass consumption and plant mortality in the Mediterranean (Fernández-García et al., 2018a), temperate (Parks et al., 2014), boreal (Soverel et al., 2011) and tropical ecosystems (Rozario et al., 2018). Despite the possibility of calculating burn severity indices with satellites allowing planetary coverage such as MODIS (Veraverbeke et al., 2011; Rahman et al., 2018), there are not yet available products of burn severity at the global scale, which would be useful to make advances in the fire and CO₂ sciences.

In this work we present a new burn severity database based on MODIS Terra and Aqua satellites. The presented database (MODIS burn SEVerity: MOSEV) provides monthly

burn severity data (dNBR, RdNBR and post-burn NBR) with global coverage since 2000 at 500 m spatial resolution. Additionally, this work describes the algorithm to develop the database, and we compared the MOSEV burn severity data with their Landsat-8 equivalents.

2 MOSEV database

2.1 Input data

The MOSEV database was built using the following remote sensing data available since November 2000 as input (Fig. 1).

- *All scenes of MODIS Terra MOD09A1 and Aqua MYD09A1 version 6.* Terra MOD09A1 and Aqua MYD09A1 scenes are 8 d composites with seven surface reflectance bands and quality information at a spatial resolution of 500 m and global coverage. The reflectance value of each pixel is the best possible observation in the 8 d period, selected according to quality criteria including cloud cover, cloud shadow, solar zenith and aerosol loading.
- *All scenes of MCD64A1 version 6 product.* MCD64A1 is a monthly 500 m pixel product that contains daily global information on burn date, uncertainty in burn date, quality assurance indicators, and first and last day of the year of reliable change detection.

MOD09A1, MYD09A1 and MCD64A1 data were downloaded from the Land Processes Distributed Active Archive Center (LP-DAAC): <https://lpdaac.usgs.gov/> (last access: 1 November 2020).

2.2 Pre-processing

Terra MOD09A1 and Aqua MYD09A1 scenes were masked to remove water bodies, glaciers, clouds and snow. Masks were obtained directly from the MOD09A1 and MYD09A1 quality bands (surface reflectance 500 m band quality control flags). Likewise, MOD09A1 and MYD09A1 scenes not registering land surface were removed from subsequent analysis.

2.3 Algorithm overview

The method to obtain burn severity indices was structured in two steps (Fig. 1): (i) calculation of dense time series of the normalized burn ratio (NBR) from merged Terra MOD09A1 and Aqua MYD09A1 scenes; and (ii) selection of the pre- and post-fire NBR for each burned pixel and calculation of differenced burn severity indices (dNBR and RdNBR).

2.3.1 Calculation of dense time series of the normalized burn ratio (NBR)

The normalized burn ratio (NBR) spectral index was calculated for each Terra MOD09A1 and Aqua MYD09A1 scene

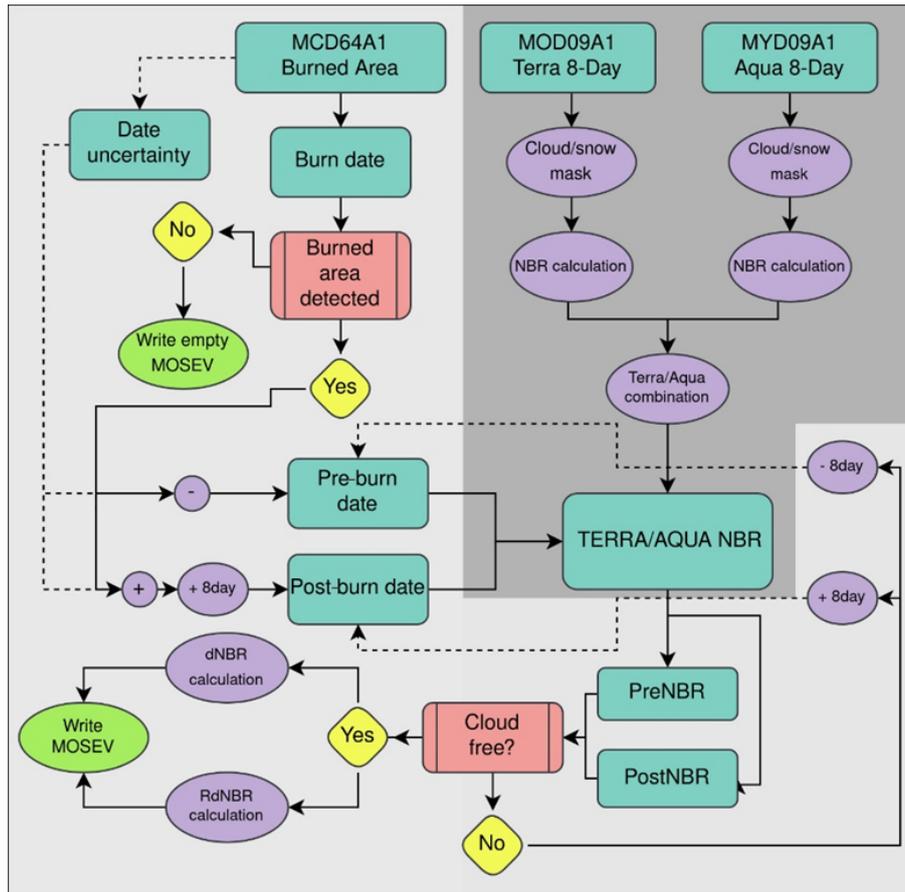


Figure 1. Methodology flow chart used for building the MOSEV database (2000–present). MOD09A1 and MYD09A1 are 8 d reflectance products at 500 m spatial resolution from MODIS Terra and Aqua respectively. MCD64A1 is the monthly MODIS burned area product at 500 m spatial resolution. NBR, dNBR and RdNBR are burn severity spectral indices (normalized burn ratio, difference of the NBR and relativized dNBR respectively).

according to the formula proposed by López-García and Caselles (1991) (Eq. 1). Terra NBR gaps (masked areas) were re-filled with the synchronous Aqua NBR values when available. The combination of Terra and Aqua imagery is useful to reduce cloud contamination and therefore increase the data availability and decrease uncertainty (Yu et al., 2015; Muhammad and Thapa, 2021). Thus, we obtained Terra–Aqua NBR composites with global coverage and a temporal resolution of 8 d from November 2000 onwards.

$$NBR_{MODIS} = \frac{(\rho_2 - \rho_7)}{(\rho_2 + \rho_7)} \times 1000, \tag{1}$$

where ρ_2 and ρ_7 are the land surface reflectance values of bands 2 (841–876 nm) and 7 (2105–2155 nm) from Terra MOD09A1 and Aqua MYD09A1 scenes.

2.3.2 Selection of the pre- and post-burn NBR and calculation of burn severity indices

BA locations and dates were obtained from the MCD64A1 product. With the burn date and uncertainty in days, and con-

sidering the 8 d nature of our Terra–Aqua NBR, we have selected the immediate pre-burn (Eq. 2) and post-burn (Eq. 3) Terra–Aqua NBR dates for each MCD64A1 burned pixel.

$$\begin{aligned} \text{preNBR date} &< \text{MCD64A1 burn day} \\ &- \text{MCD64A1 uncertainty in days} \end{aligned} \tag{2}$$

$$\begin{aligned} \text{postNBR date} &> \text{MCD64A1 burn day} \\ &+ \text{MCD64A1 uncertainty in days} + 8 \text{ d} \end{aligned} \tag{3}$$

When NBR values for the immediate pre-burn NBR date were not available (see Sect. 2.2), the previous NBR image was selected. In contrast, when NBR values for the immediate post-burn date were not available, the next NBR image was selected. These processes were repeated until pre- and post-burn NBR values were detected for each burned pixel on a cell by cell basis.

We have obtained the pre-burn NBR value and the post-burn NBR value from the pre- and post-fire Terra–Aqua NBR dates which were used to calculate the dNBR and RdNBR value for each burned pixel of the MCD64A1 product. Both

dNBR and RdNBR are bi-temporal spectral indices that account for the change caused by fire in NIR and SWIR reflectance.

The dNBR index is the reference burn severity spectral index used by the European Forest Fire Information System (<https://effis.jrc.ec.europa.eu/about-effis>, last access: 1 May 2021) and by the Monitoring Trends in Burn Severity programme of the USA (<https://www.mtbs.gov>, last access: 1 May 2021), and it was calculated according to Key and Benson (2006) (Eq. 4), dNBR values increasing with burn severity.

$$\text{dNBR} = \text{preNBR} - \text{postNBR} \quad (4)$$

Likewise, RdNBR is also an outspread burn severity spectral index used by the Monitoring Trends in Burn Severity programme of the USA (<https://www.mtbs.gov/>, last access: 1 May 2021). RdNBR was calculated according to Miller and Thode (2007) (Eq. 5), higher RdNBR values indicating higher burn severity.

$$\text{RdNBR} = \frac{\text{dNBR}}{\sqrt{\frac{|\text{preNBR}|}{1000}}} \quad (5)$$

2.4 Implementation

Burn date from MCD64A1, pre-burn NBR date, post-burn NBR date, pre-burn NBR, post-burn NBR, dNBR and RdNBR have been written in monthly scenes since November 2000 at a spatial resolution of 500 m (MOSEV database). All operations to calculate and write the database were carried out in the R programming language using the *rspatial/luna* (Ghosh et al., 2020) and *terra* (Hijmans et al., 2020) libraries and Bash Unix shell command language. All the calculations and data manipulation were performed at the supercomputing facilities of the Spanish Research Council (CSIC).

2.5 Comparison with Landsat burn severity indices

In order to evaluate the MOSEV database, we have compared MOSEV burn severity indices (dNBR, RdNBR and post-burn NBR) with the same indices manually obtained from higher-spatial-resolution imagery. To perform the comparison, we have selected Landsat scenes which have 30 m spatial resolution and have been the most used imagery for burn severity assessments (Key and Benson, 2006; Fernández-García et al., 2018a). We selected 13 regions of 185 km × 180 km (Landsat-8 tile dimension) with a large extent of BA and which are randomly distributed across the globe (See Table A1 in the Appendix). Pre- and post-burn consecutive scenes (16 d span) with low cloud cover (< 25 %) of the Landsat-8 Collection 1 Level-2 product were selected for each region and downloaded from the USGS Earth Explorer (<https://earthexplorer.usgs.gov/> last access: 1 Novem-

ber 2020). Landsat-8 Collection 1 Level-2 scenes are composed of seven land surface reflectance bands at a spatial resolution of 30 m and a quality band which was used to mask cloud covered areas. Bands 5 (850–880 nm) and 7 (2110–2290 nm), which are comparable to MODIS bands 2 (841–876 nm) and 7 (2105–2155 nm), were aggregated and resampled averaging the Landsat values to the MODIS grid in order to match the spatial resolution of the MOSEV products (500 m). Landsat-8 resampled bands were used to calculate the pre-burn NBR and the post-burn NBR (Eq. 6), as well as the dNBR (Eq. 4) and RdNBR (Eq. 5) spectral indices.

$$\text{NBR}_{\text{OLI}} = \frac{(\rho_5 - \rho_7)}{(\rho_5 + \rho_7)} \times 1000, \quad (6)$$

where ρ_5 and ρ_7 are the land surface reflectance values of Landsat-8 bands 5 (850–880 nm) and 7 (2110–2290 nm) resampled to the spatial resolution of MOSEV products.

To assess the relationships between the burn severity indices included in the MOSEV database with the same ones derived from Landsat-8, we sampled all available burned pixels ($n = 32\,163$) of the 13 study regions from both MOSEV and Landsat-8 dNBR, RdNBR and post-burn NBR layers (Table A1). Then, we performed scatterplots, and we calculated the Pearson's correlation coefficients (R) and the significance of the correlations (P).

3 Data description

The MOSEV database (doi:10.5281/zenodo.4265209, Alonso-González and Fernández-García, 2020) is composed of monthly scenes from November 2000 onwards with a spatial resolution of 500 m. The scenes are organized following the tiling system of MODIS (sinusoidal tile grid). In total, the database is structured in 246 non-overlapping tiles that cover an area of $10^\circ \times 10^\circ$ on the Equator (Fig. 2). The name of each MOSEV scene encodes the year, Julian day indicating the month and MODIS tile. For instance, the MOSEV A2019305.h31v11 scene corresponds to the year 2019, month of November (month ended on the Julian day 305) and h31v11 MODIS tile.

Each MOSEV scene is composed of seven layers (Table 1; Fig. 3): dNBR, RdNBR, pre-burn NBR, post-burn NBR, pre-burn selected date, post-burn selected date and the burn date from MCD64A1. In all layers we assigned the values of $-32\,767$ to unburned land, $32\,767$ to water bodies and $-18\,000$ to those areas where it was not possible to fill with a severity value or the severity value was out of the allowed range.

- *dNBR*. The valid range in the MOSEV database corresponds to their mathematical feasible range (-2000 to 2000) (see Eq. 4), although values above 1200 are not usual (Key and Benson, 2006).
- *RdNBR*. The valid range in the MOSEV database was bounded from -4000 to 4000 since values outside these

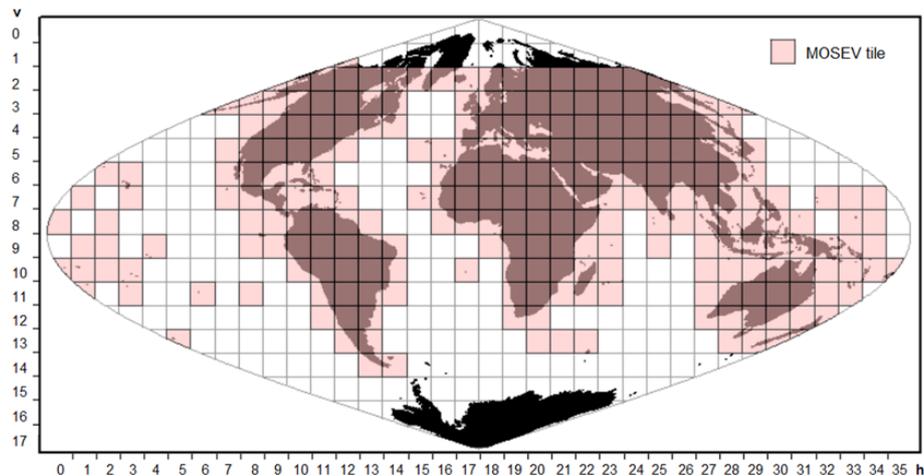


Figure 2. MODIS sinusoidal tiling system and available MOSEV tiles.

Table 1. Layers of the MOSEV product.

Layer	Units	Type	Valid range	Unburned land	Water	No data
dNBR	Unitless	16 bit	−2000 to 2000	−32 767	32 767	−18 000
RdNBR	Unitless	16 bit	−4000 to 4000	−32 767	32 767	−18 000
preNBR	Unitless	16 bit	−1000 to 1000	−32 767	32 767	−18 000
postNBR	Unitless	16 bit	−1000 to 1000	−32 767	32 767	−18 000
preburn_selected_date	Cycles	16 bit	≥ 0	−32 767	32 767	−18 000
postburn_selected_date	Cycles	16 bit	≥ 0	−32 767	32 767	−18 000
burndate_from_MCD64A1	Days	16 bit	1 to 366	−32 767	32 767	−18 000

limits are feasible (see Eq. 5) but anomalous (Miller and Thode, 2007; Miller et al., 2009).

- *Pre- and post-burn NBR.* Both spectral indices are the Terra–Aqua composites used in the calculation of dNBR and RdNBR. Likewise, the post-burn NBR is the most common mono-temporal burn severity spectral index, its value decreasing as burn severity increases. The pre- and post-burn NBR valid range in the MOSEV database corresponds to their mathematically feasible range (−1000 to 1000) (see Eq. 1).
- *Pre- and post-burn selected dates.* These are estimators of the pre- and post-burn NBR dates and represent the number of iterations necessary to find available pre- and post-burn NBR values. Specifically, a value of 0 in the selected date indicates that the NBR date is the immediate NBR according to the Eq. (2) (pre-burn) and Eq. (3) (post-burn). A value of 1 indicates that the immediate NBR value was not available, and the previous (in the case of the pre-fire) or the next (in the case of post-fire) NBR value was used instead.
- *Burn date from MCD64A1.* This is the date of burning in Julian days registered in the MCD64A1 BA product.

It was used as the basis for identifying the pre- and post-burn selected dates and pre- and post-burn NBR values.

In order to reduce the overall size of the database, the MOSEV scenes where no fires were detected are composed of a single empty layer entitled “burndate_from_MCD64A1”. We did it in this way in order to maintain the same number of MOSEV files per tile even in the unburned scenarios, similar to the original MCD64A1 product. Each MOSEV file is a multi- or single-band GeoTIFF in 16-bit integers, compressed using the lossless compression algorithm Lempel–Ziv–Welch (LZW). The MOSEV scenes are distributed as a zipped file, constituted by all the scenes of each tile. The complete dataset can be freely downloaded at <https://doi.org/10.5281/zenodo.4265209> (Alonso-González and Fernández-García, 2020).

4 Results and discussion

In this work we have developed the MOSEV product, which is a global burn severity database based on MODIS Terra and Aqua surface reflectance and MODIS BA products. The database includes dNBR, RdNBR and NBR burn severity indices at 500 m pixel size, which are usually calculated at local scale using higher-resolution imagery, traditionally with

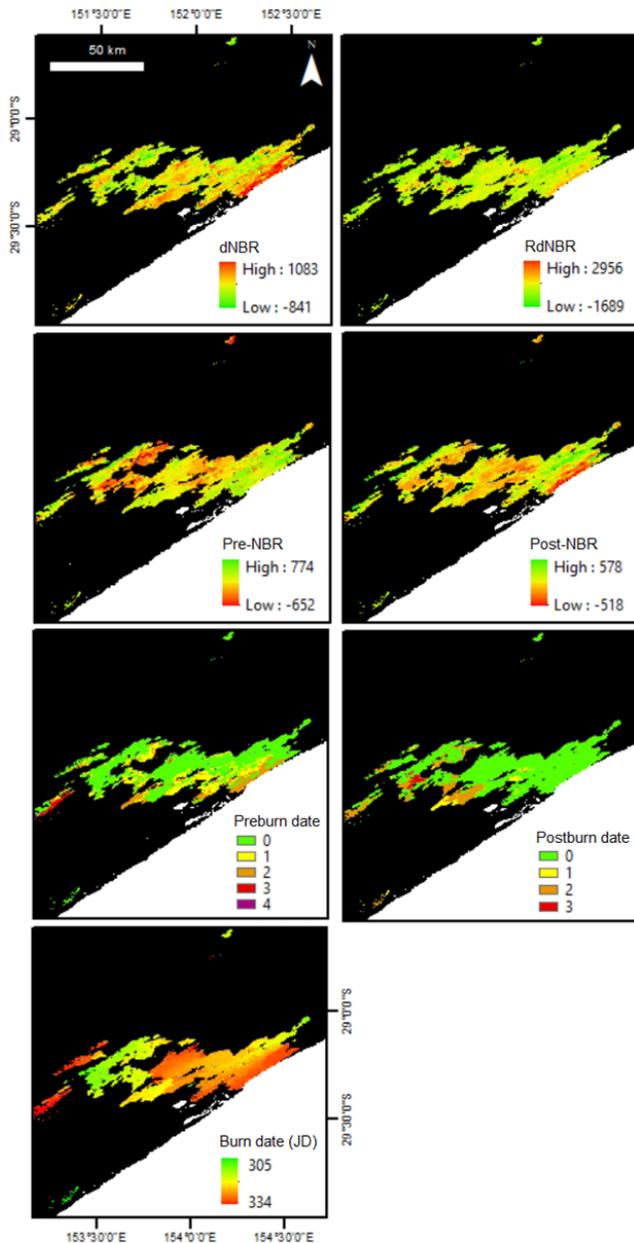


Figure 3. Example of the layers included in a MOSEV scene (A2019305.h31v11) representing some of the 2019 wildfires in Australia (New South Wales). Spectral indices dNBR, RdNBR, pre-NBR and post-NBR are unitless. The pre-burn and post-burn dates indicate the number of cycles or iterations necessary to find available NBR values (each cycle added to 0 corresponds to a difference of 8 d). The burn date is expressed in Julian days. White areas are water bodies (value of 32 767), and black areas are unburned land (value of $-32\,767$).

Landsat scenes (Chuvienco, 2010; Key and Benson, 2006; Miller and Thode, 2007; Fernández-García et al., 2018a) and more recently with Sentinel-2 scenes (Fernández-Manso et al., 2016).

4.1 Comparison with Landsat burn severity indices

The probability density functions of MOSEV and Landsat burn severity indices (dNBR, RdNBR and post-burn NBR), as well as their relationships, are shown in Fig. 4. In general, results showed a high similarity between MOSEV and Landsat probability density functions, with values more concentrated to the mean for Landsat indices and a slight negative bias for the three spectral indices as MOSEV mean values tended to be lower than those in Landsat data (Table 2). MOSEV and Landsat burn severity indices were highly correlated ($P < 0.001$) for the three burn severity indices. Specifically, the post-burn NBR showed a higher correlation coefficient ($R = 0.88$) than dNBR ($R = 0.74$) and RdNBR ($R = 0.42$).

Previous research has found discrepancies in surface reflectance when comparing both MODIS and Landsat satellites (Feng et al., 2013; Veraverbeke et al., 2011; Ke et al., 2015; Potapov et al., 2020). These differences could be explained by several reasons. (i) The higher temporal resolution of MODIS imagery used to build the database enables us to use pre-fire information very close to the burning event. This has a significant influence on the pre-burn NBR values, which typically decrease as the fire season approaches and when drought conditions are more severe (Wang et al., 2008). This fact explains the lower pre-burn NBR values and the higher proportion of negative values in the MOSEV product compared with Landsat (Fig. A1, Table A2) which unavoidably lead to some differences in dNBR and RdNBR values and could contribute to a higher proportion of negative values in these indices in the MOSEV database (Table 2). Also the post-fire information in the MOSEV product is very close to the burning event, thus potentially allowing a better assessment of burn severity compared with the lower temporal resolution of the Landsat constellation. (ii) There are potential errors in radiometric gains from Landsat imagery, which are used for rescaling digital numbers to radiance values (Chander et al., 2009). (iii) Saturation problems in bright surfaces have been detected by Feng et al. (2013) in Landsat imagery but not for MODIS. This effect may influence the quality of the pre-fire NIR and the post-fire SWIR reflectance, which have high values in severely burned areas (Key and Benson, 2006). (iv) Differences in imagery pre-processing may affect the final reflectance values. In this sense, Landsat imagery is resampled using a cubic convolution method (uses 16 nearest-neighbour data points) in the geometric correction stage (Landsat 8 Data Users Handbook Version 5.0, 2019), whereas MODIS reflectance products are resampled using bilinear interpolation (four nearest-neighbour data points) (MODIS Science Data Support Team, 1997). The use of cubic convolution method smooths reflectance values more than bilinear interpolation, contributing to moderate extreme values. This assumption is supported by the probability density functions (Fig. 4) which show a higher abundance of extreme values for the spectral indices when calculated from

Table 2. Mean values and proportion of positive and negative values of the burn severity spectral indices included in the MOSEV database (dNBR, RdNBR and post-burn NBR spectral indices) and the equivalent obtained from 13 Landsat-8 scenes randomly distributed across the globe ($n = 32\,163$).

Layer	MOSEV (mean)	Landsat (mean)	MOSEV (% positive)	Landsat (% positive)	MOSEV (% negative)	Landsat (% negative)
dNBR	210.3	216.7	92.0	98.8	8.0	1.2
RdNBR	616.0	651.5	92.0	98.8	8.0	1.2
postNBR	-68.4	-54.7	27.4	29.4	72.6	70.6

MODIS instead of Landsat. Similarly, it was necessary to re-sample the Landsat products to the MODIS grid to make it comparable considering the big resolution shift, introducing some obvious and unavoidable uncertainty.

Likewise, we detected variability in the correlations between MOSEV and Landsat among the three studied burn severity indices. The higher correspondence of the pre-burn and post-burn NBR spectral indices suggests that the mono-temporal approach contributes to achieve higher correlations (see post-NBR in Fig. 4 and pre-NBR in Fig. A1). In contrast, combining the information of two scenes (bi-temporal approach) entails higher differences in satellite reflectance and therefore in bi-temporal spectral indices (dNBR and RdNBR). Focusing on dNBR and RdNBR, we found higher correlations between MOSEV and LANDSAT dNBR than RdNBR, which can be the direct consequence of the RdNBR algorithm (see Eq. 5) as low pre-burn NBR absolute values may cause really high and even anomalous RdNBR values, generating heteroscedasticity (see Fig. 4). However, in general both burn severity products showed good levels of agreement considering the unavoidable uncertainties associated with the very different nature of Landsat and MODIS. Thus, the comparison of MOSEV and Landsat burn severity proves the consistency of the developed algorithm, the dNBR relationships being similar (Veraverbeke et al., 2011) or even better (Rahman et al., 2018) than those found in previous studies that compared retrieved burn severity information from both products.

4.2 Indices interpretation and validity

NBR, dNBR and RdNBR spectral indices were developed to provide optimum measurements of fire effects and biomass consumption from multispectral imagery (Key and Benson, 2006; Miller and Thode, 2007). The three indices are based on the change caused by burning on NIR and SWIR reflectance. NIR reflectance is highly sensitive to canopy density, being lower in burned than in vegetated areas. In contrast, SWIR reflectance is sensitive to moisture content and ash and is significantly higher in burned areas than in vegetated zones. The NBR index (López-García and Caselles, 1991) uses this information to estimate burn severity from a mono-temporal approach. In general, high positive NBR values indicate vegetated areas, whereas bare soil and burned

areas present low and usually negative NBR values: the more negative, the more severely burned. The validation of burn severity indices has been widely addressed using Landsat imagery and field measurements at a similar spatial resolution (~ 30 m) because of the high difficulty of taking accurate field measurements at coarser spatial scales. The most popular field measurements to assess the performance of burn severity spectral indices are those indices based on the composite burn index (CBI) (Key and Benson, 2006), which combines information on fuel consumption and related changes caused by fire, including plant mortality, char height and soil colour. In general, the literature shows high variability in the goodness-of-fit between NBR- and CBI-type indices. For instance, Picotte and Robertson (2011) found R^2 values ranging from 0.61 to 0.86 in different ecosystems across North America the following months after fire; De Santis and Chuvieco (2009) reported R^2 values between 0.32 and 0.66, largely varying depending on the CBI-type index used; and Fernández-García et al. (2018a) obtained R^2 values between 0.69 and 0.88 for different forest ecosystems on the Iberian Peninsula. Although NBR has a proven capacity to indicate burn severity, it is usually overcome by differenced indices such as the dNBR and RdNBR, which account for the pre-burn conditions (Key and Benson, 2006; Fernández-García et al., 2018a).

The dNBR and RdNBR indices provide quantitative measurement of the environmental change between the pre- and post-burn situation (i.e. biomass consumption and related changes) (Key and Benson, 2006). The dNBR is a measurement of severity understood as absolute change, whereas the RdNBR was designed to relativize the dNBR to the pre-fire situation; thus, the total combustion of areas with different amounts of vegetation would lead to similar RdNBR values, but dNBR would be higher in the most vegetated area (Miller and Thode, 2007). The performance of both dNBR and RdNBR indices obtained from Landsat has been validated in numerous studies across the globe. For instance, Zhu et al. (2006) reported mean R^2 values of 0.67 (dNBR) and 0.60 (RdNBR) when correlating CBI in different ecosystems in North America; Parks et al. (2014) found mean R^2 values of 0.76 (dNBR) and 0.77 (RdNBR) in the western United States; Fernández-García et al. (2018a) used a CBI-type index to analyse the goodness-of-fit of both dNBR ($R^2 = 0.81$)

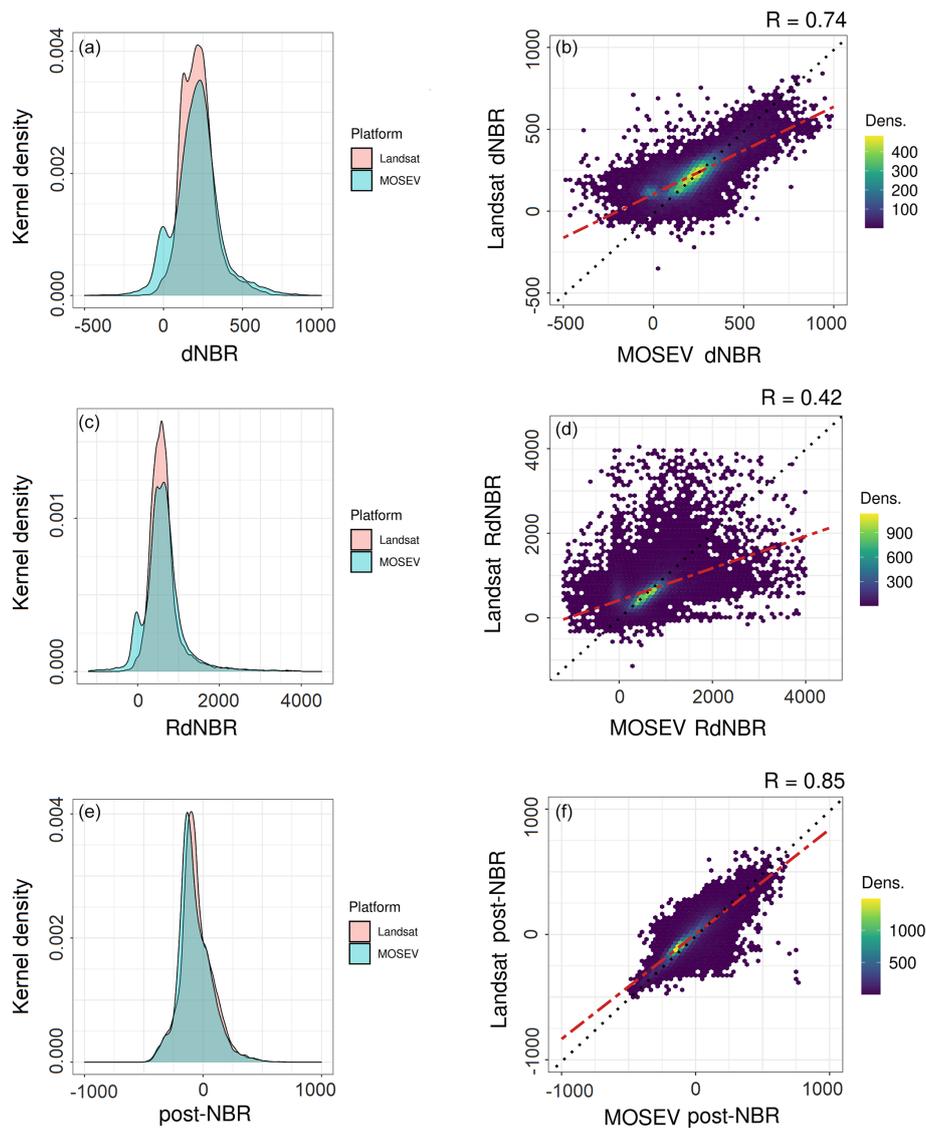


Figure 4. Gaussian kernel densities (a, c, e) and scatterplots (b, d, f) showing the relationships between the burn severity data included in the MOSEV database (dNBR, RdNBR and post-burn NBR spectral indices) and the equivalent data obtained from 13 Landsat-8 scenes randomly distributed across the globe ($n = 32\,163$). R is Pearson's correlation coefficient, and Dens. signifies density of points. See Table A1 for further information.

and RdNBR ($R^2 = 0.78$) indices in forest ecosystems on the Iberian Peninsula; Cai and Wang (2020) found a better performance of dNBR ($R^2 = 0.84$) than RdNBR ($R^2 = 0.79$) when correlating a descriptive burn severity index in southeast China; and Rozario et al. (2018) found that dNBR ($R^2 = 0.56$) and RdNBR ($R^2 = 0.58$) indices were able to indicate the percentage of scorched vegetation in tropical dry forests of Costa Rica.

The values of both dNBR and RdNBR increase proportionally to burn severity, and in general, values below zero indicate unburned or recovered areas. The dNBR and RdNBR continuous data can be used to differentiate burn severity categories. The number of classes and burn severity thresholds

is entirely up to the user's objective, and empirical thresholding based on the relationships with field data is useful to provide ecological meaning to the spectral-index-based categories (Key and Benson, 2006; Fernández-García et al., 2018b). An option when field data are not available is to define thresholds according to the literature (Rozario et al., 2018). In this sense, Key and Benson (2006) provided six dNBR thresholds to differentiate seven burn severity categories, whereas Miller and Thode (2007) provided three thresholds (41, 176 and 366 for dNBR; 69, 315 and 640 for RdNBR) to differentiate unchanged, low, moderate and high severities in forest ecosystems of North America with the post-fire image taken 1 year after fire. Preferred thresh-

old values are higher when the post-fire image is closer to the fire date (Key and Benson, 2006), as is the case of MOSEV indices. Examples of thresholds in forest ecosystems with the post-fire images taken immediately after fire are those provided by Botella-Martínez and Fernández-Manso (2017) which differentiated unburned, low, moderate and high with three threshold values (160, 260 and 481 for dNBR; 230, 475 and 835 for RdNBR).

4.3 Advancements and limitations

The main asset of the MOSEV database is that it is the first global burn severity database which complements the existing global BA data such as the FireCCI50 (Chuvieco et al., 2018) or the MCD64A1 C6 products (Giglio et al., 2018). One of the most important strengths of MOSEV is a consequence of MODIS revisit time (1 to 2 d), which is shorter than Landsat-8 (16 d) and Sentinel-2 (5 d). This high temporal resolution allowed us to obtain dense free-cloud NBR time series that can be indispensable to calculate burn severity indices in regions of persistent cloud cover. In fact, Ju and Roy (2008) show that the probability of finding two consecutive Landsat scenes within a month is 0.63 globally but near 0 in many regions such as Russia and Canada and many areas of Central Africa among others. Likewise, another improvement of MOSEV burn severity indices over indices calculated from other satellites such as Landsat or Sentinel is the higher temporal consistency of the data, as Terra and Aqua satellites have used the same MODIS sensor since 2000.

The main limitation of the MOSEV database is related to its spatial resolution of 500 m, which impedes accounting for fine-grain spatial heterogeneity. However, this spatial resolution enables the study of burn severity at regional and planetary scale with low computational costs. Another fact to consider is the error in the classification of burned areas in the MCD64A1 BA product on which MOSEV is based. In this sense, Giglio et al. (2018) reported a global commission error (CE) of 24 % and an omission error (OE) of 37 %, whereas Boschetti et al. (2019) in a stage-3 validation indicated a global CE of 40 % and an OE of 73 %. The lowest errors were detected in regions where fires are larger and fire scars persistent, such as in boreal forests.

4.4 Potential applications

Burn severity metrics from the MOSEV database can be useful to analyse temporal trends in burn severity, to study the global spatial patterns of burn severity, to identify areas where the post-fire recovery of soil and vegetation can be endangered and to enhance global models of carbon emissions, among other applications. In addition, it will constitute a cost-effective way of monitoring the global burn severity in a close to real time way as MOSEV could be upgraded to the same temporal frequency as the MCD64A1 product.

In relation to the temporal trends of burn severity, it is common in the fire ecology literature to assume increases in burn severity owing to climate change (e.g. García-Llamas et al., 2019; Moreira et al., 2020). However, there is little evidence of that at the planetary scale since there was no global burn severity data. Previous studies in that line have analysed temporal trends in burn severity at the regional scale, mainly in the USA and Europe (Fried et al., 2004; Parks et al., 2016; Picotte et al., 2016). With the MOSEV database it is possible to study global trends in burn severity and study relationships between burn severity and global change.

Spatial patterns of fire occurrence and burn severity have also captured the interest of several researchers (e.g. Duffy et al., 2007; Kennedy and Johnson, 2014; Stevens et al., 2017), but research at the global scale is limited to the study of BA (Andela et al., 2017). Thus, the MOSEV database opens the possibility of expanding the study of fire patterns to the planetary scale including the variable burn severity.

Burn severity is a variable of high interest to predict ecosystem responses (Keeley, 2009). Among the most relevant ecosystem responses for forest managers is soil erosion (De Luis et al., 2003) and vegetation recovery (Fernández-García et al., 2018b, 2019, 2020). Thus, MOSEV burn severity indices may serve as a tool for land managers to roughly identify target areas for post-fire forest management, as well as to study predictors of burn severity which could be useful for pre-fire management (García-Llamas et al., 2019).

Moreover, previous work has shown the importance of including burn severity metrics as predictors of CO₂ emissions caused by fires (e.g. Veraverbeke et al., 2015; van der Werf et al., 2017). The MOSEV database will be useful for the enhancement of global CO₂ emission models.

5 Data availability

The MOSEV database is freely downloadable at <https://doi.org/10.5281/zenodo.4265209> (Alonso-González and Fernández-García, 2020).

6 Conclusions

We have introduced the newly developed MOSEV database, which is the first burn severity database with global coverage, available from November 2000 onwards. The algorithm used to build the database is based on MODIS Terra and Aqua surface reflectance imagery, as well as on the MCD64A1 BA product. MOSEV data include seven layers at 500 m pixel size with the most commonly used burn severity spectral indices (dNBR, RdNBR and post-burn NBR), the pre-burn NBR, estimators of the date of the pre- and post-burn MODIS surface reflectance scenes used for calculations and the date of burning. The burn severity indices from MOSEV showed consistent relationships with Landsat-derived burn severity indices, which have been the most used for burn severity as-

assessments. Thus, this database could be the basis to accomplish future studies of burn severity at the global scale in a computationally cost-effective way, as well as research on where burn severity could be a relevant factor such as in forest management and CO₂ emissions research.

Appendix A

Table A1. Scenes and number of pixels (*n*) used to compare MOSEV and Landsat-8-derived (L8) burn severity indices (dNBR, RdNBR and post-burn NBR).

Location	<i>n</i>	MOSEV scene	Pre-burn L8 scene	Post-burn L8 scene
Brazil	450	MOSEV.A2019213.h11v09	LC082320652019081201T1-SC20200607111702	LC082320652019082801T1-SC20200607111630
Nepal	1082	MOSEV.A2019121.h25v06	LC081430402019050901T1-SC20200607111858	LC081430402019052501T1-SC20200607111838
USA	133	MOSEV.A2019274.h08v05	LC080370362019100901T1-SC20200607111820	LC080370362019102501T1-SC20200607111815
Russia	2188	MOSEV.A2019182.h24v02	LC081170172019072201T1-SC20200607111752	LC081170172019080701T1-SC20200607111749
Senegal	9245	MOSEV.A2019032.h16v07	LC082040512019021301T1-SC20200607111948	LC082040512019021301T1-SC20200607111808
Kazakhstan	2091	MOSEV.A019244.h22v03	LC081510252019092201T1-SC20200607111850	LC081510252019100801T1-SC20200607111857
Zambia	8863	MOSEV.A2019182.h20v10	LC081730702019071401T1-SC20200607111924	LC081730702019073001T1-SC20200607111814
Bolivia	83	MOSEV.A2019182.h11v10	LC080010712019070901T1-SC20200607111740	LC080010712019072501T1-SC20200607111831
Canada	17	MOSEV.A019182.h12v02	LC080610152019062701T1-SC20200607111838	LC080610152019071301T1-SC20200607111857
South Africa	371	MOSEV.A2019001.h19v12	LC081750842019010101T1-SC20200607111855	LC081750842019011701T1-SC20200607111857
Kazakhstan	5130	MOSEV.A2019182.h23v04	LC081520272019071101T1-SC20200607111844	LC081520272019072701T1-SC20200607111833
Mozambique	1103	MOSEV.A2019213.h21v10	LC081670742019080501T1-SC20200607111843	LC081670742019082101T1-SC20200607111845
Russia	1407	MOSEV.A2019091.h19v03	LC081880222019040201T1-SC20200607111738	LC081880222019041801T1-SC20200607111829
Total	32 163			

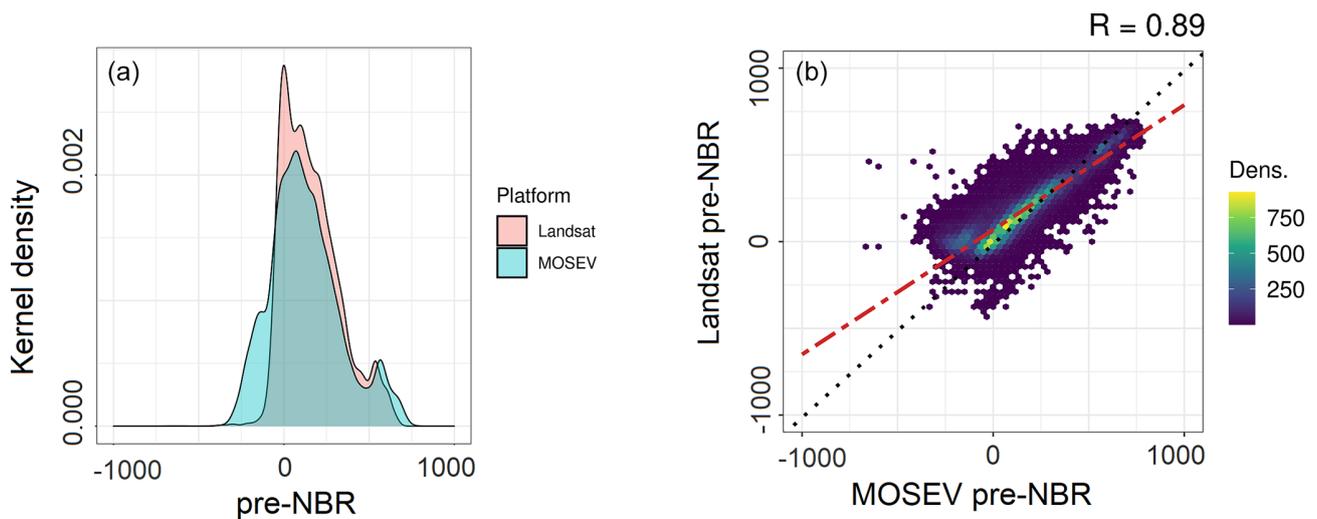


Figure A1. Gaussian kernel densities (a) and scatterplots (b) showing the relationships between the pre-burn NBR spectral index included in the MOSEV database and the equivalent obtained from 13 Landsat-8 scenes randomly distributed across the globe ($n = 32\ 163$). *R* is Pearson’s correlation coefficient, and Dens. signifies density.

Table A2. Mean values and proportion of positive and negative values of the pre-burn NBR spectral index included in the MOSEV database and the equivalent obtained from 13 Landsat-8 scenes randomly distributed across the globe ($n = 32\ 163$).

Layer	MOSEV (mean)	Landsat (mean)	MOSEV (% positive)	Landsat (% positive)	MOSEV (% negative)	Landsat (% negative)
preNBR	128.5	161.0	72.2	82.7	27.8	17.3

Author contributions. EAG and VFG designed the database and the structure of the manuscript. EAG developed the algorithms and the MOSEV database. VFG prepared the Landsat-8 data. EAG did the statistical analysis of the data. EAG and VFG made the figures. VFG wrote the first draft of the manuscript, and EAG contributed to writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Review statement. This paper was edited by David Carlson and reviewed by two anonymous referees.

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