Scanner derived colour parameters to determine suspended sediment sources in burned catchments

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1. INTRODUCTION

After a wildfire, total or partial removal of vegetal biomass and changes in physicochemical soil properties can lead to an increase in overland flow and sediment yield (Shakesby and Doerr, 2006). Eventual damage must be counteracted urgently identifying erosion hotspots, implementing post-fire management programmes and sampling campaigns to check its effectiveness.

Under this context, the sediment source fingerprinting technique is widely used for determining the origin of suspended sediments in catchments (Collins et al., 2017) and can be useful to evaluate the effectiveness of sediment management programmes. It traditionally relies on the use of physical, biochemical and geochemical properties as tracers. However, measuring these tracers in the laboratory often entails a high economic cost and time consuming.

Colour tracers were proven to greatly reduce this cost and measuring time, especially if measurements are done using a common office scanner (Pulley and Rowntree 2016). Here we propose that colour parameters can be used to investigate SS origin in burned catchments.

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2. OBJECTIVES

We advance the proposition that suspended sediment colour can inform about the relative contribution of burned and unburned surfaces in river catchments. Suspended sediment tracing results in a Mediterranean burned catchment obtained using an ordinary office scanner were compared with those obtained (i) using colour parameters estimated from reflectance diffuse spectrometry and (ii) ^{137}Cs and ^{210}Pb$_{ex}$ fallout radionuclides, as to investigate its consistency.

3. STUDY AREA

The Sa Font de la Vila River is a Mediterranean catchment of 4.8 km^2 located in Andratx municipality (western of Mallorca Island, Spain; Fig. 1A and 1B) which is affected by the extensive afforestation of former agricultural land and recurrent wildfires

The average temperature is 16.5 °C. The mean annual rainfall is 518 mm yr^{-1}, with an inter-annual coefficient of variation of 29%.

The catchment has been affected by two major wildfires, which occurred in 1994 and 2013 (Fig. 1C). The 2013 fire affected 71% of the catchment After the last wildfire The Balearic Islands Department of Environment implemented a series of post-fire strategies to prevent soil loss and degradation, which included mulching, tree planting and the creation of log barriers with dead biomass.
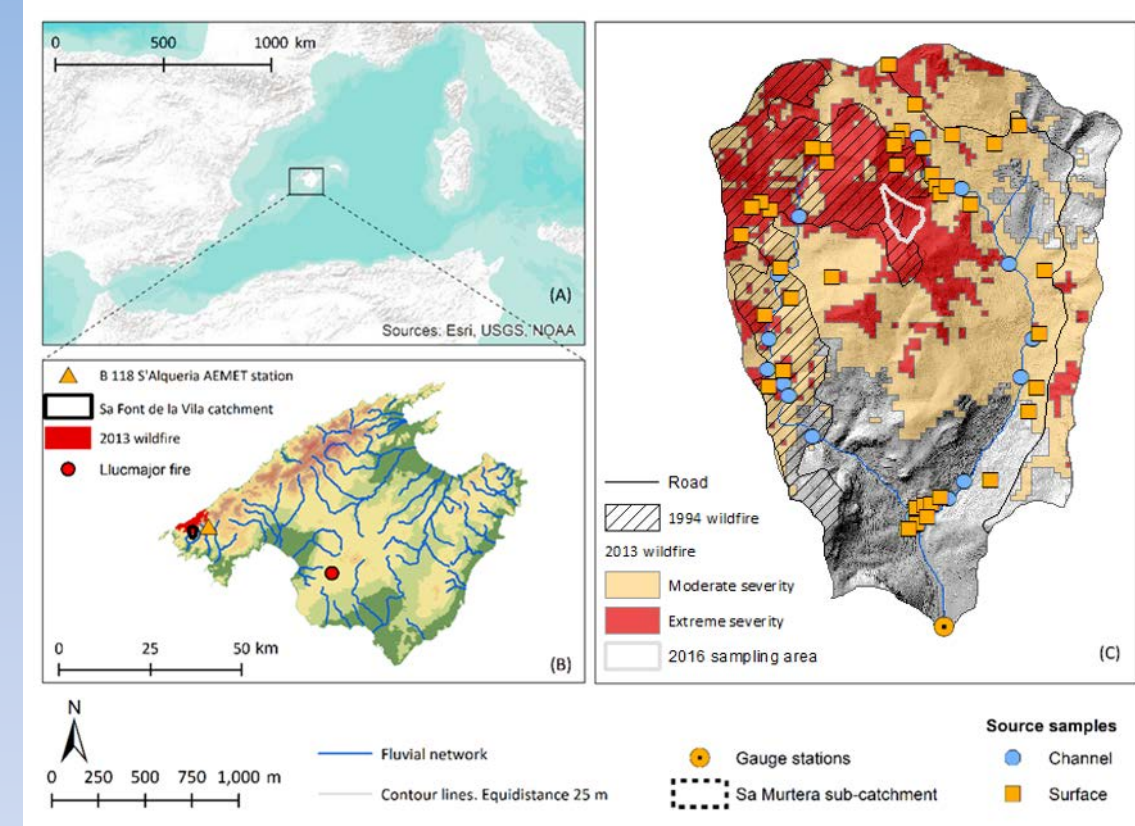

Figure 1. Location of the Mallorca Island within the Mediterranean Sea (A); location of the Sa Font de la Vila catchment, the area affected by the July 2013 wildfire, the B'12 S'Alqueria meteorological station and the village of Llucmajor (B); and 1994 and 2013 wildfire affected areas as well as severity of the 2013 wildfire (E). Channel bank and surface sampling points indicated as blue dots and orange squares, respectively.

4. METHODS

4.1. Soil, ash and sediment sampling

Samples of potential sediment sources were collected immediately after the last wildfire (**September 2013**; Fig. 2) on soil hillslopes with an apparent active sediment slope-to-channel connectivity (0-2 cm depth; *n= 40*) and potential erodible channel banks (*n= 20*). The surface sample collection strategy was designed considering **burned** (*n= 31*) and **unburned** areas (*n= 9*).

Suspended sediment samples (*n= 5*) were collected during the hydrological years comprised between 2013 and 2015 using time integrated samplers (Phillips et al., 2000).

Ashes were collected from a fire affected area in August 2018 (southwest of Mallorca; Fig. 1B). This burned site showed similar soil type, climate and vegetation.

In a simplified procedure, the ash samples were combined in two groups representing the overall gradient of ash colours, namely the black ashes (*n= 10*), including the darker samples, and the grey ashes (*n= 9*), including the lighter samples

Figure 2. Study area status in during the source sampling campaign

4. METHODS

4.2. Laboratory treatment and analysis

Samples were dried at 40°C, disaggregated and sieved them <63 μm. The particle size distribution (PSD) and the specific surface area (SSA) were determined by using a Malvern Mastersizer. ^{137}Cs and ^{210}Pb$_{ex}$ activity concentrations (Bq·kg^{-1}) were measured by gamma using a high-purity coaxial intrinsic germanium detector. Total C and N were measured by high-temperature combustion using a TruSpec CHNS, LECO.

All the samples were placed in transparent plastic bags (Fig. 3) and scanned with an office scanner (Konika Minolta bizhub C554). Red, green and blue colour parameters (i.e. RGB model) were extracted from the scanned images using the GIMP 2 open source image editing software. Then, the ColoSol software, developed by Viscarra Rossel (Viscarra Rossel et al., 2006), was used to estimate the Munsell HVC (i.e. Munsell H, Munsell V and Munsell C), CIE XYZ (i.e. cie X, cie Y and cie Z) , CIE LAB (cie L, cie a* and cie b*), CIELUB (i.e. cie L, cie u* and cie v*), CIELHC (i.e. cie L, cie H and cie C), and decorrelated RGB (i.e. HRGB, IRGB and SRGB) colour parameters, as well as the redness index (i.e. RI) and Helmoltz chromaticity coordinates (i.e. DW nm, Pe %).
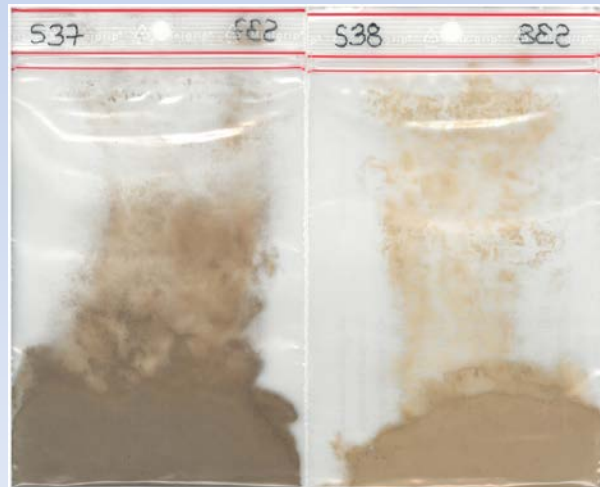

Figure 3. Samples scanned within transparent plastic bags

4. METHODS

4.2. Laboratory treatment and analysis

Diffuse reflectance measurements were taken in a dark room using spectroradiometer (ASD FieldSpect-II; Fig 4). Following the International Commission on Illumination (CIE, 1931), CIE xyY colour coefficients were computed from the spectra reflectance measurements as well as the RGB colour values. Then, the procedure described in the previously to obtain the rest of colour parameters.

Ash exhaustion and soil recovery over time could alter the source colour values. However, sources where only sampled once (1 month after the fire). To partially mitigate this limitation, we made use of 24 soil samples collected in 2016 (29 months after the fire) in a headwater field within the study site (Figure 1C). Samples were collected following the same methodology than in 2013 and scanned to measurer its colour parameters. These samples were initially collected to analyse soil quality parameters after a wildfire in Calsamiglia et al. (2017) and Lucas-Borja et al. (2018).

Figure 4. Spectroradiometer used to measure soil, sediment and ash samples diffuse reflectance

4. METHODS

4.3. Artificial laboratory mixtures

30 artificial mixtures of 2, 3 and 4 different samples were created to test the linear additivity of the colour tracers and the influence of ash. Mixtures were made from different source samples (i.e. channel bank, unburned surface and burned surface), ash (grey and black) and suspended sediment. To investigate the ash influence on the colour parameters, 18 artificial samples mixing suspended sediment and ash (black and grey) in different proportions were created. The ash proportion was gradually modified from 10% to 90% to check the influence of the ash on the sediment colour variation (Fig. 5).
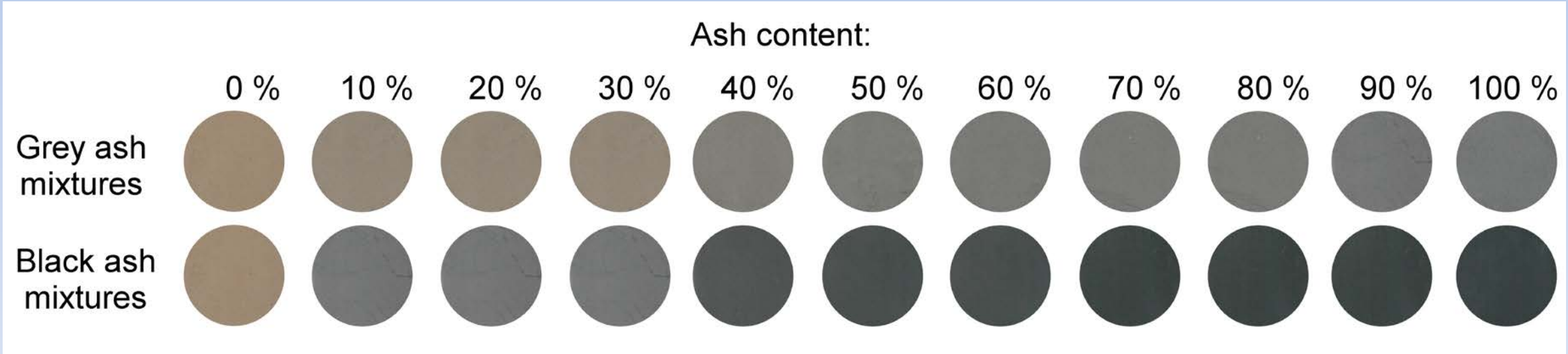

Figure 5. Scanned sediment-ash artificial samples

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4. METHODS

4.4. Accuracy of colour tracers

The individual accuracy and linear additivity behaviour of colour tracers were assessed by comparing measured values (i.e. spectrometer- and colour-based) with predicted values in artificial mixtures by means of a mass balance approach.

In order to compare colour tracers with different scales, the normalized root mean square error (nRMSE) was calculated by dividing the RMSE by the mean of the measured data. The nRMSE was expressed as a percentage. The tracers with a nRMSE >15% were discarded.

A Kruskal-Wallis H test was performed to test the ability of the colour tracers to discriminate between the different sediment source groups. Then, a Discriminant Function Analysis (DFA) was performed to check the discriminating potential of each group of colour tracers.

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4. METHODS

4.5. Suspended sediment fingerprinting and unmixing of artificial mixtures

A range test was used to exclude potentially non-conservative tracers for each individual suspended sediment sample.

MixSIAR Bayesian tracer mixing model framework (Stock et al., 2018), implemented by Stock and Semmens (2016) as an open-source R package, was used to estimate the relative contribution of each source to the suspended sediment samples and the artificial mixtures.

The fundamental mixing equation of a mixing model is:

$$b_i = \sum_{j=i}^{m} w_j \cdot a_{i,j}$$

where b_i is the tracer property i (i = 1 to n) measured in a suspended sediment sample, $a_{i,j}$ is the value of the tracer property i in each source sample j (j = 1 to m), w_j is the unknown relative contribution of each source j to the suspended sediment sample.

The Markov Chain Monte Carlo parameters were set as very long: chain length = 1,000,000, burn = 700,000, thin = 300, chains = 3. Convergence of the models was evaluated using the Gelman-Rubin diagnostic

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5. RESULTS

5.1. Artificial laboratory mixtures and ash influence

Colour parameters showed individual contrasting performance to predict the colour of artificial mixtures (Table 1).

	Spectrometer-based parameters	Scanner-based parameters
Linear additivity test:		
Colour parameters with **nRMSE < 15%**	cie x, cie y, red, green, blue, HRGB, IRGB, cie L, cie H, Munsell H, Munsell V, DW nm, Pe %	cie x, cie y, green, blue, IRGB, cie L, Munsell V, DW nm

Table 1. Scanner and spectrometer-based parameters that pass the artificial mixture additivity test.

Accuracy of scanner-based and spectrometer-based colour parameters was similar. Accordingly, colour parameters calculated using the two independent techniques were highly correlated ($n = 24$; confidence limit 99%; $P < 0.01$).

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5. RESULTS

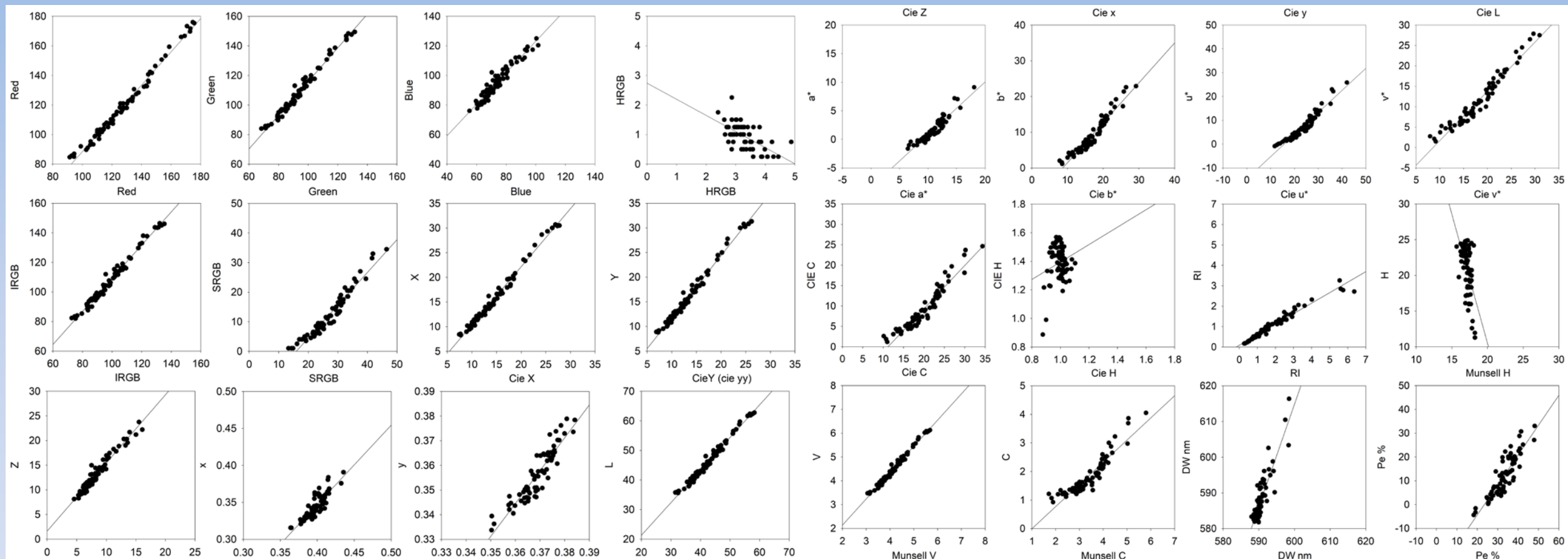## 5.1. Artificial laboratory mixtures and ash influence

Figure 7. Scatter plots showing scanner and spectrometer-based colour parameters correlations

5. RESULTS

5.1. Artificial laboratory mixtures and ash influence

A clear evolution of colour parameters was observed when adding regular proportions of ash to a suspended sediment sample; i.e., from 10 to 90%.

Mixtures with black ash showed larger errors compared to grey ash mixtures. Grey ash mixtures nRMSE errors for red, green and blue were < 10% (Figure 8D). On the contrary, for black ash mixtures showed > 10% nRMSEs (Figure 8D).
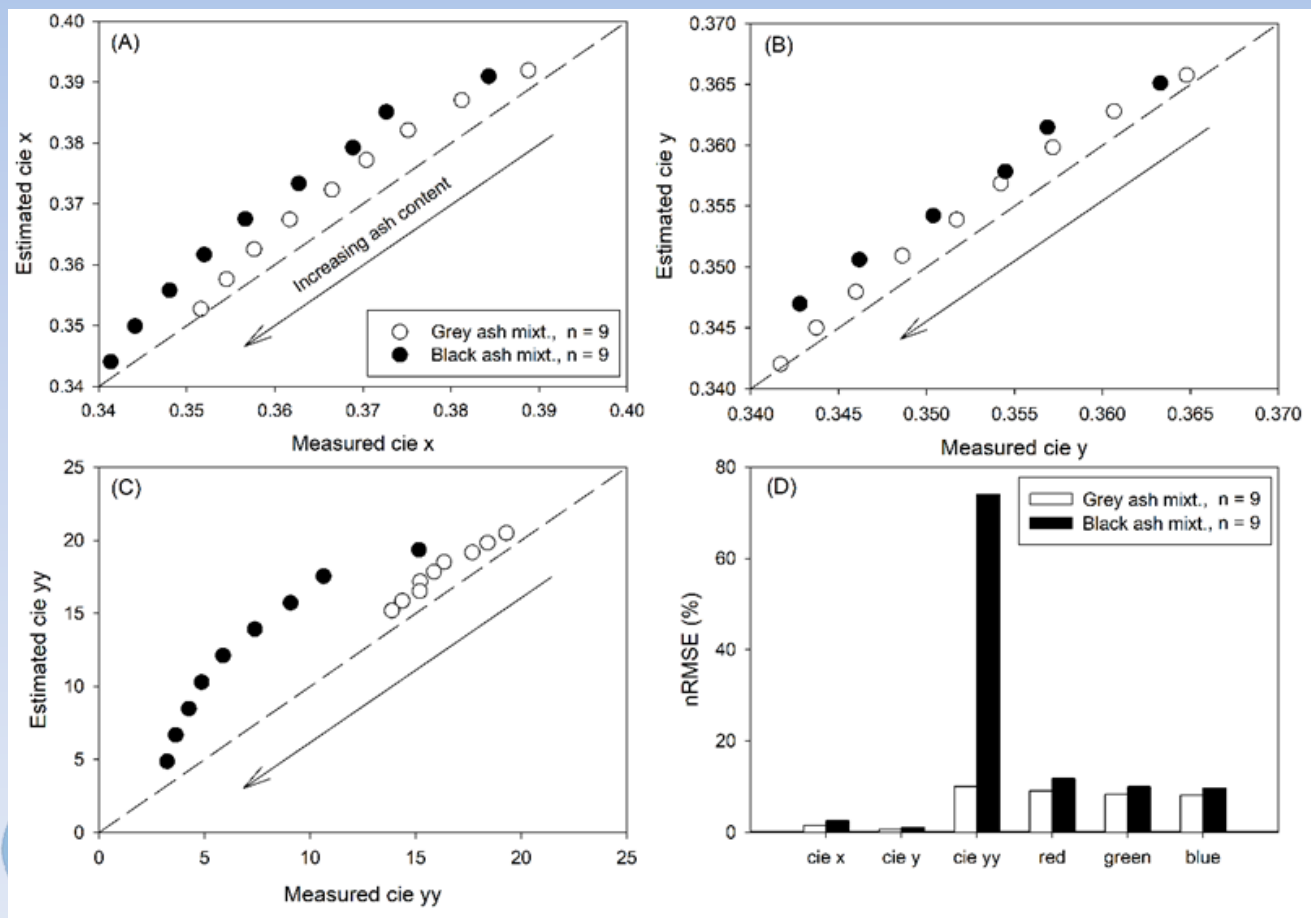
Errors were lower with large contribution of one of the samples to the mixture (i.e. lower deviation from the identity line in Figures 8A, 8B and 8C), whereas errors increased if proportion of both samples mixed was similar.

Figure 8. Scatter plots showing estimated versus measured cie x (A), cie y (B) and cie yy (C) spectrometer-based colour parameter when adding increasing proportions of ash

5. RESULTS

5.2. Colour, particle size, organic matter content and FRNs activity of sources, ash and suspended sediment samples

Samples from distinct sources depicted distinct colour values ($p < 0.05$, K-Wallis H test; see an example of three scanner-based colour parameter distribution in sources and sediment and ash samples in Fig. 10)

The DFA results considering all the independent variables together were that the spectrometer-based parameters correctly classified the 78.3 % of the source samples and with scanner-based parameters and 80% for spectrometer-based parameters (leave-one-out cross-validation).

The particle size distribution analysis was carried applying a Mann-Whitney U test. All source samples groups showed statistical similarity with the suspended sediment samples.
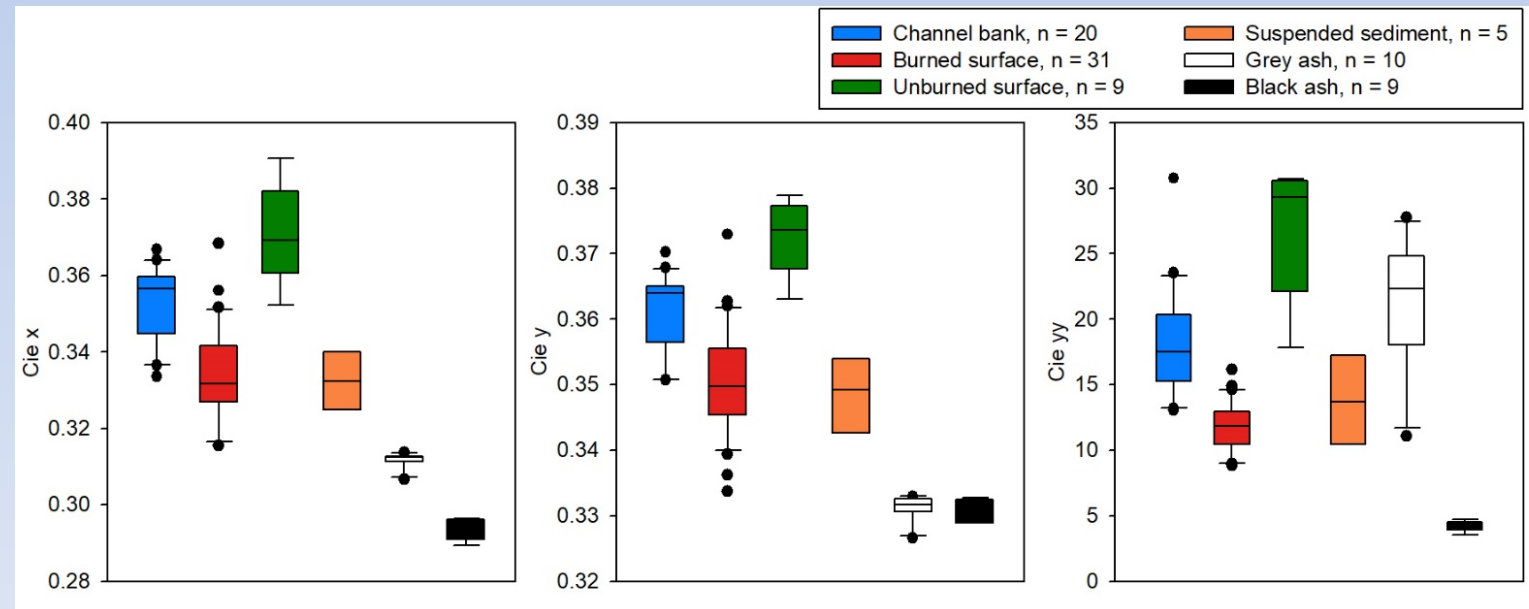

Figure 9. Box plots of cie x, cie y and cie yy scanner-based colour parameters measured in source and suspended sediment samples. Values measured on grey and black ashes are plotted for comparison.

5. RESULTS

5.2. Colour, particle size, organic matter content and FRNs activity of sources, ash and suspended sediment samples

Burned surface samples showed the highest average activity values for ^{137}Cs and ^{210}Pb$_{ex}$ (Table 2).

Channel bank and unburned surface samples presented very similar average FRNs activities. These samples did not pass the K-Wallis distribution test (p > 0.05) and were grouped into a single source (i.e. referred as unburned-channel).

Both FRNs passed the K-Wallis test when considering as sources burned surface and unburned-channel. Suspended sediment samples activity fall within the range of the sources.

Tracers	Sample groups	Mean (Bq kg^{-1})	Sta.Dev.
^{210}Pb$_{ex}$	Channel bank	46.377	40.814
	Burned surface	204.138	98.312
	Unburned surface	42.045	52.376
	Suspended sediment	177.835	102.389
^{137}Cs	Channel bank	6.260	3.803
	Burned surface	28.665	16.076
	Unburned surface	5.811	6.118
	Suspended sediment	20.800	8.754

Table 2. Average Fallout radionuclide (FRNs) activity (Bq kg^{-1}) in the different source and sediment sample groups.

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5. RESULTS

5.3. Suspended sediment fingerprinting

All colour tracers that surpassed the linear additive test also passing the range test (spectrometer and scanner-based colour parameters

Changes over time in the predicted suspended sediment sources were observed after apply de MIxSIAR model.

DS1a and **DS1b** were collected in parallel during the same event (29/10/2013). Using **scanner-based colour parameters**, the mixing models predicted a clear contribution of burned soil with 84.4% ± 5.7 and 81.3% ± 7.5, respectively (Table 3, next slide)

The predominant source was still burned soil for the next sample (**DS2**) with a contribution of 53% ± 10.7

For the **DS3** sample, the predicted predominant source changed towards unburned soil with a predicted contribution of 65.9% ± 17.4

Finally, for the **DS4** sample, the mixing models predict that the main suspended sediment source was again burned (49% ± 7.9), followed by unburned soil (34.4% ± 9.7)

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5.3. Suspended sediment fingerprinting

		Scanner		Spectrometer		FRNs	
DS1a	Burned surface	**88.4 ± 5.7**	75.2 - 97.5	**84.6 ± 6.4**	70.9 - 96	**85.8 ± 10.3**	62.4 - 99.5
	Unburned surface	4.4 ± 3.4	0.2 - 12.8	5.7 ± 4.2	0.3 -15.9	14.2 ± 10.3	0.5 - 37.6
	Channel bank	7.2 ± 5.8	0.2- 21.8	9.7 ± 6.8	0.4 - 25.5		
DS1b	Burned surface	**81.3 ± 7.5**	65.3 - 94.8	**86.2 ± 6.1**	73.3 - 96.7	**70.3 ± 16**	40 - 97.8
	Unburned surface	6.5 ± 4.7	0.3 - 17.2	5.1 ± 3.9	0.2 - 14.6	29.7 ± 16	2.2 - 60
	Channel bank	12.2 ± 8.4	0.5 - 30.4	8.7 ± 6.2	0.4 - 23		
DS2	Burned surface	**53 ± 10.2**	31.7 - 70.9	**53.8 ± 8.7**	36.8 - 70.3	**72.7 ± 15.3**	43.5 - 98.1
	Unburned surface	19 ± 10	1.4 - 38.1	19.8 ± 10	1.6 - 38	27.3 ± 15.3	1.9 - 56.5
	Channel bank	27.9 ± 17.2	1.4 - 63.1	26.4 ± 15.7	1.9 - 58.3		
DS3	Burned surface	8.6 ± 7.1	0.2 - 26	20.3 ± 9.5	2.1 - 38.2		
	Unburned surface	**65.9 ± 17.4**	21.2 - 91.3	**65 ± 10.5**	**45 - 84.2**	No data	
	Channel bank	25.4 ± 20	1 - 75.1	14.7 ± 12.9	0.5 - 44.9		
DS4	Burned surface	28.4 ± 15.4	3 - 56.5	**49 ± 7.9**	32.7 - 63.3	38.4 ± 19.8	7.9 - 86.4
	Unburned surface	19.6 ± 162	0.5 - 52	34.4 ± 9.7	9.8 - 50.4	**61.6 ± 19.8**	13.6 - 92.1
	Channel bank	**52.1 ± 29.1**	1.6 - 91.8	16.6 ± 13.8	0.6 - 52.9		

Table 3. MixSIAR source apportionment using scanner-based colour parameters, spectrometer-based colour parameters and fallout radionuclides activity (FRNs). It should be note that Unburned surface and channel bank sources were in the same group for FRNs results

5. RESULTS

5.3. Suspended sediment fingerprinting

Comparing the MixSIAR predictions obtained using different groups of tracers (i.e. scanner-based, spectrometer-based colour parameters and FRNs), the three tracer groups predicted the same dominant source in all samples except one (DS4; Table 3).

The 2016 samples showed scanner-based colour values that range between the burned soil and the unburned soil samples (Figure 11A and 11B). A

new MixSIAR unmix was performed using the colour parameters measured in the 2016 soil samples as burned sources instead of the samples collected in 2013. The results (Figure 11B and 11C) were similar in both cases, with an average absolute error of 5.7 ± 6.6%.
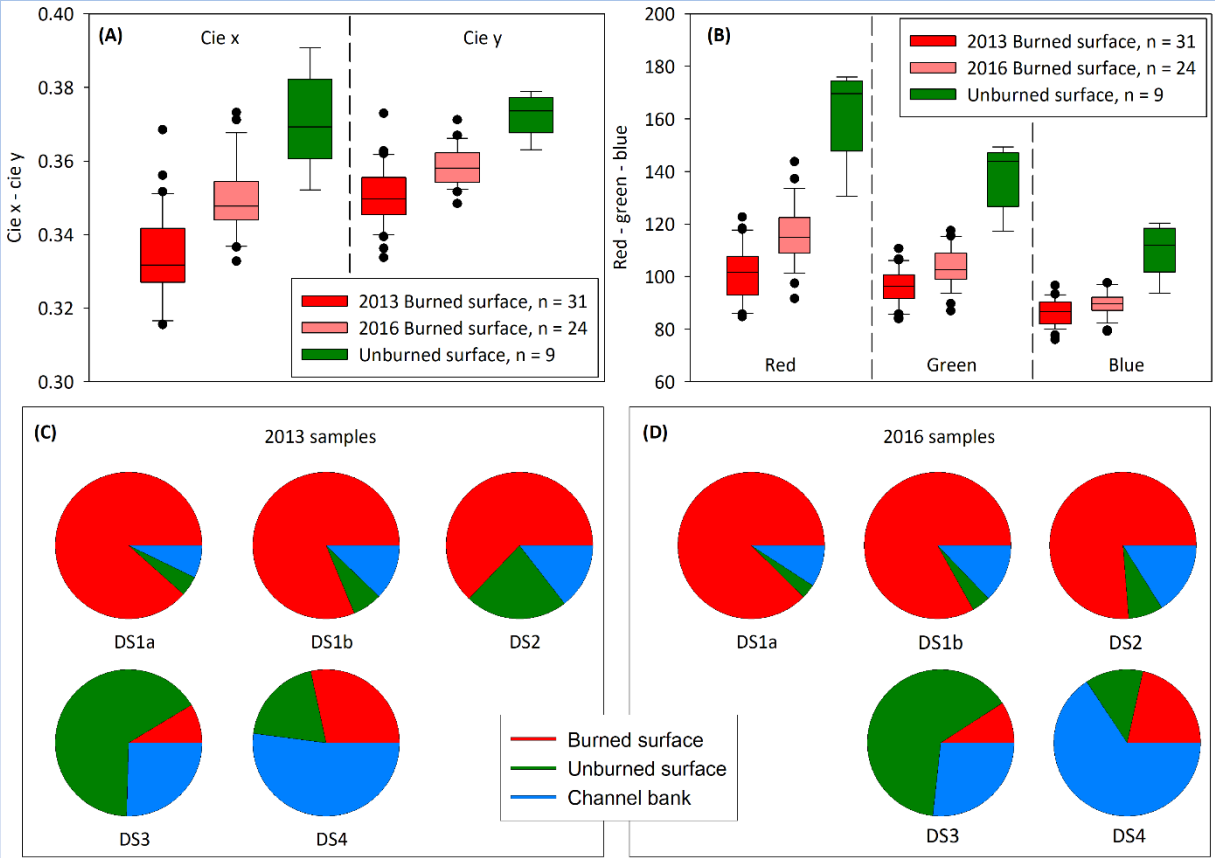

Figure 11. (A) Box plots of cie x and cie y and (B) RGB scanner-based colour parameters measured in 2013 burned source samples, 2016 burned source samples and 2013 unburned source samples; (C) MixSIAR source apportionment using 2013 burned surface scanner-based colour parameters; (D) MixSIAR source apportionment using 2016 burned surface scanner-based colour parameters.

5. CONCLUSIONS

Colour tracers measured using scanner have been proved to be consistent tracers to discriminate between burned and unburned sediment sources.

Colour parameters can then be used together with unmixing approached to provide suspended sediment tracing data after wildfires in small Mediterranean catchments, as our results are consistent with tracing results obtained using the well-stablished radionuclides.

The main advantage of colour parameters is that they can be measured fast using cheap and non-destructive methods. Hence, allowing quick definition of eventual post-fire management strategies.

Nevertheless, results must be carefully considered and cross-checked using other tracers. This might be even more important in burned catchments, where ash exhaustion and soil recovery during the disturbance period may influence colour parameters. Accordingly, variations in organic matter content and differences in particle size distribution are to be addressed.

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