Fire effects on soil aggregate stability: a review and synthesis

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Fire can affect soil properties depending on a number of factors including fire severity and soil type. Aggregate stability (AS) refers to soil structure resilience in response to external mechanical forces. Many authors consider soil aggregation to be a parameter reflecting soil health, as it depends on chemical, physical and biological factors. The response of AS to forest fires is complex, since it depends on how fire has affected other related properties such as organic matter content, soil microbiology, water repellency and soil mineralogy. Opinions differ concerning the effect of fire on AS. Some authors have observed a decrease in AS in soils affected by intense wildfire or severe laboratory heating. However, others have reported increases. We provide an up to date review of the research on this topic and an analysis of the causes for the different effects observed. The implications for soil system functioning and for the hydrology of the affected areas are also discussed. Generally, low severity fires do not produce notable changes in AS, although in some cases an increase has been observed and attributed to increased water repellency. In contrast, high severity fires can induce important changes in this property, but with different effects depending on the type of soil affected. The patterns observed can vary from a disaggregation as a consequence of the organic matter destruction, to a strong aggregation if a recrystallization of some minerals such as Fe and Al oxyhydroxides occurs when they are present in sufficient quantities in the soil, after exposure to high temperatures.

Fig. 1. Soil surface after a high severity wildfire in Pinoso, Alicante, SE Spain (J. Mataix-Solera, 2003). The high degree of the combustion in a high severity fire produces the elimination of vegetal cover, litter and organic horizons. The exposition of the mineral leads AS as a key factor controlling topsoil hydrology, crust development and erodibility.

Fig. 4. Water drops (arrowed) on the surface of a water-repellent aggregate. Photo by Jorge Mataix-Solera and Vicky Arcenegui, 2011.

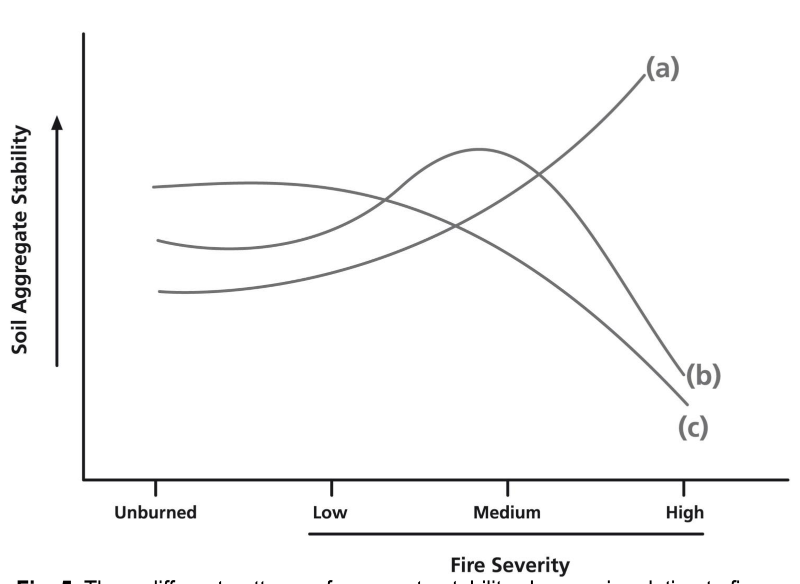

Fig. 5. Three different patterns of aggregate stability changes in relation to fire severity: a) soil with a high clay content, calcium carbonate, Fe and Al oxides as principal cementing substances; b) soil with organic matter as the principal binding agent and originally hydrophilic or with low water repellency; and c) a sandy soil highly which is water-repellent and has organic matter as the principal binding agent.

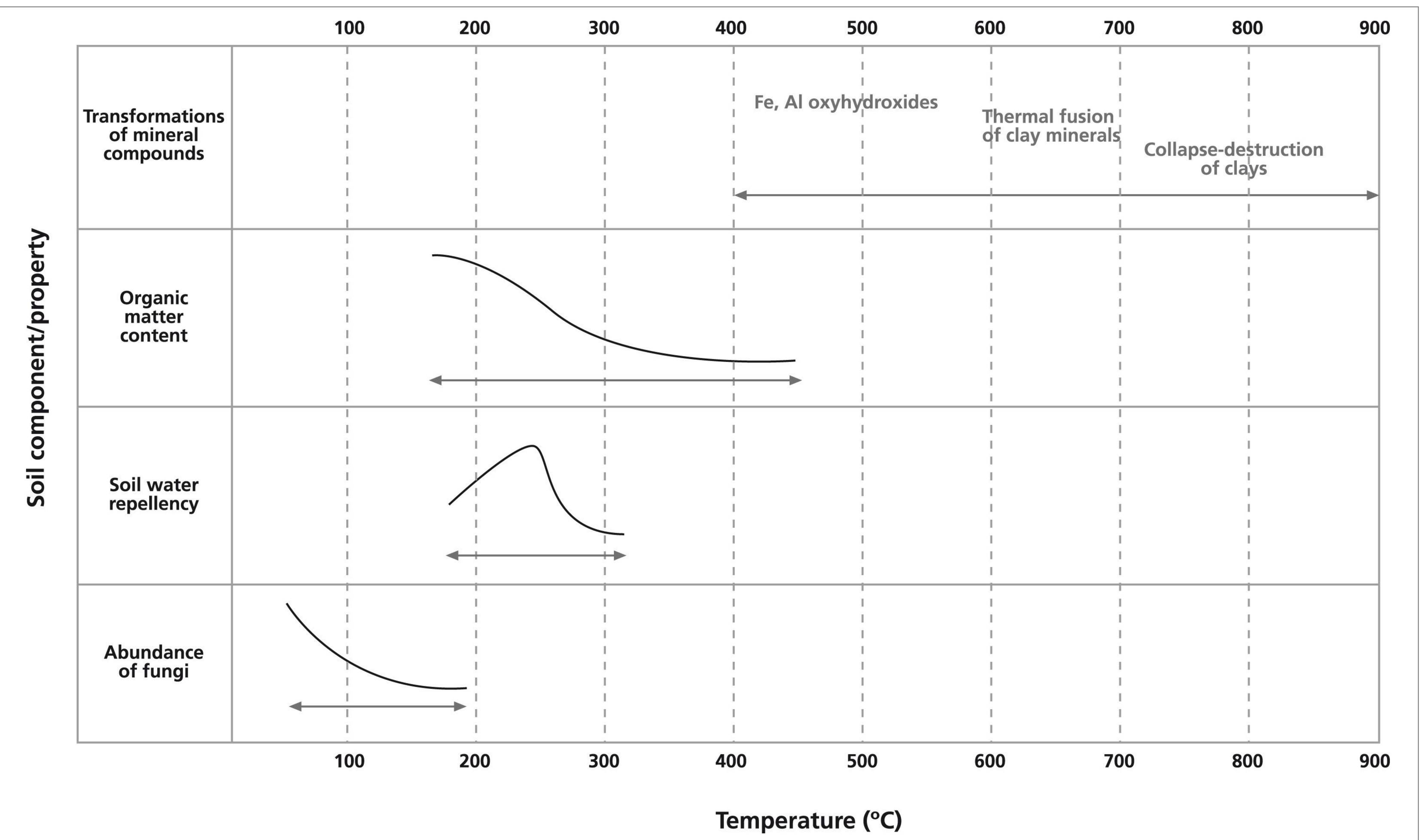

Fig. 2. The main soil components or properties relevant to aggregation and their changes at different temperatures. Horizontal lines indicate the approximate range of temperatures at ones which each property changes. The curves represent the magnitude and trend of the changes induced by fire at particular temperatures. These ranges can vary depending on the type of soil and also on the duration of a given temperature. Based in different studies (e.g.: DeBano et al., 1976; Giovannini et al., 1988; Soto et al., 1991; Neary et al., 1999; Ketterings et al, 2000; Arcenegui et al., 2007).

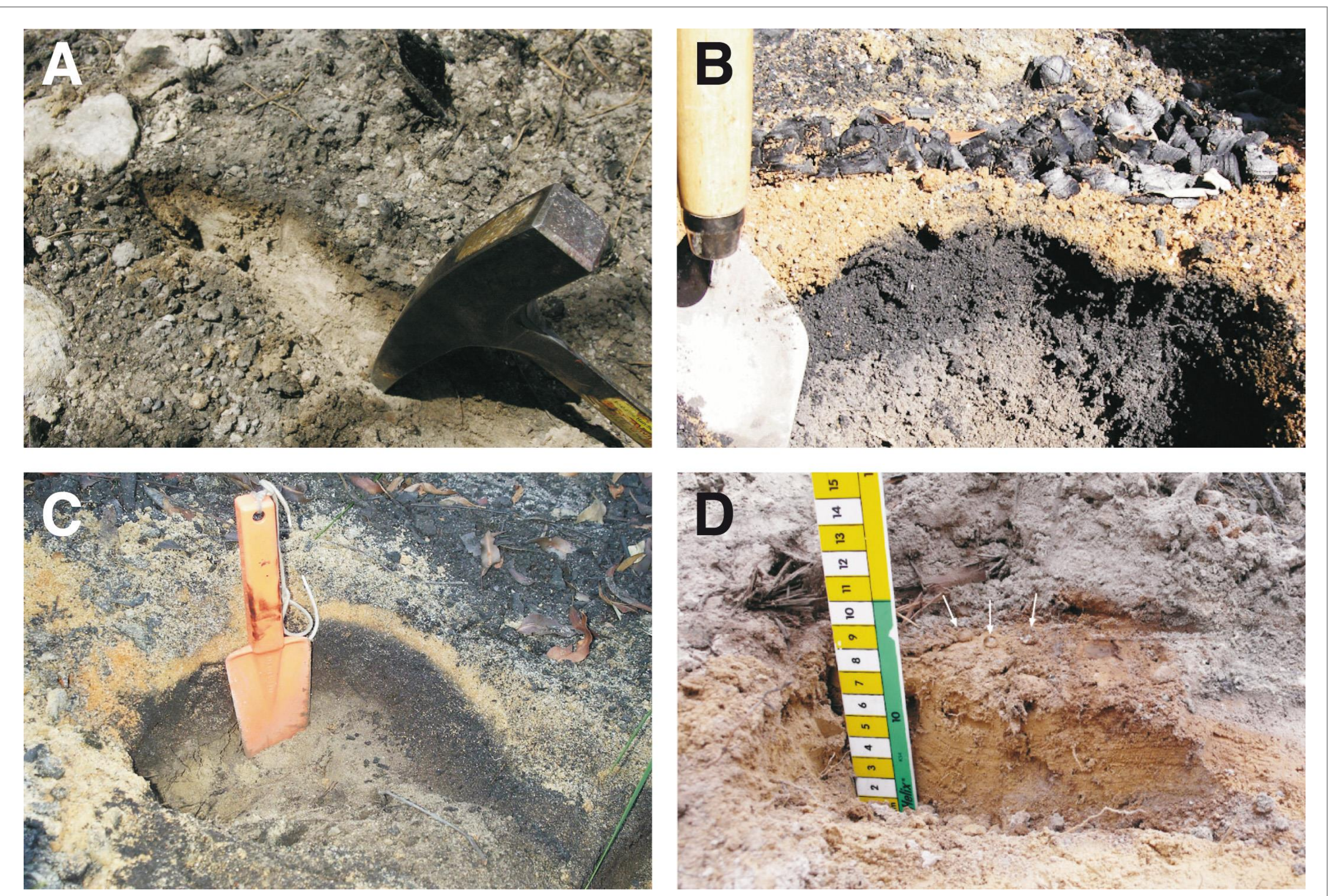

Fig. 3. The upper few centimetres of surface soil can be affected by the combustion of the litter and soil organic matter, due to the heat released during fire. This, in turn, can affect aggregate stability. The images provide examples of soil affected by fire from different forested environments. A) Organic matter in the upper few centimetres has been quantitatively and qualitatively affected. The photo was taken seven months after a moderate intensity forest fire in Finestrat, Alicante, SE Spain (J. Mataix-Solera, 2009). B) Clay loam soil affected by the 2009 Black Saturday fires near Melbourne (Australia). The soil (grey) is overlain by a thick (5cm) ash layer. At the very top, organic matter has been oxidised as indicated by the pale brown colour. The charcoal above is likely to have been deposited subsequently from charred logs. C) Sandy soil in Sydney's main water supply catchment, affected by the Christmas 2001 wildfires (Australia). The red colour suggests complete oxidation of organic matter and changes in mineralogy due to extreme heating under a burning log. D) Highly water repellent silty soil under a thick ash cover following a severe wildfire in conifer forest, Montana (USA). Arrows indicate water drops over water-repellent soil. Photos B, C and D courtesy of Stefan H. Doerr.

Table 1
Summary of results of aggregation from different studies including laboratory controlled experiments, prescribed and experimental field fires, and wildfires

Author(s)	Location	Soil type[a] / soil properties	Type of fire or burning[b]	Fire severity and/or T (ºC), time data[c]	Time after burning[d]	Aggregate stability (AS) method(s)[e]	Size of aggregates burnt vs unburnt[f] + - =	AS: burnt vs unburnt[g] + - =
Are et al. 2009	W Nigeria	Typic Kanhaplustalf[1]	PF	Low-medium	15d	WS1	-	=
Arcenegui et al. 2008	SE Spain	Xerorthents and Haploxerepts[1]	WF	Medium-high	7d	RS1	n.d.	+
Arcenegui et al. 2008	SE Spain	Haploxerolls and Rhodoxeralfs[1]	WF	Low	7d	RS1	n.d.	=
Badía & Martí 2003	NE Spain	Xeric Torriorthent[1] and Calcaric Regosol[2]	LB	250-500ºC	0d	WS1	n.d.	-
Badía & Martí 2003	NE Spain	Xeric Haplogypsid[1] and Haplic Gypsisol[2]	LB	250-500ºC	0d	WS1	n.d.	-
Boix-Fayos 1997	SE Spain	Lithic Leptosol[2]	WF	Low- High	2-3y	CND, US	=	+
Bowker et al. 2004	Oregon, USA	Non-calcareous, loam	WF	Medium	11m	WI	n.d.	-
Campo et al. 2008b	SE Spain	Rendzic Leptosol[2]	EF	High	0-360d	WS1	-	-
Campo et al. 2008b	SE Spain	Rendzic Leptosol[2]	EF	Medium	0-360d	WS1	-	=
Cerdà 1993	SE Spain	Xeralfs[1]	WF	n.d.	2y	CND, TDI	n.d.	-
Fox et al. 2007	Orleans, France	Planosol[2]	LB	≥ 150ºC	0d	WS3	n.d.	+
García-Corona et al. 2004	NW Spain	Regosols and Umbrisols[2]	LB	170-220ºC 30min	0d	CND	=	+
García-Corona et al. 2004	NW Spain	Regosols and Umbrisols[2]	LB	380-460ºC 30min	0d	CND	-	-
García-Oliva et al. 1999	Jalisco, Mexico	Orthent[1]	PF	500ºC surface	1d	WS1	n.d.	=
García-Oliva et al. 1999	Jalisco, Mexico	Orthent[1]	PF	500ºC surface	7m	WS1	n.d.	-
Giovannini & Lucchesi 1983	Sardinia, Italy	Lithic Xerochrept[1]	EF	n.d.	7d	WS1 (WSI)	n.d.	-
Giovannini & Lucchesi 1997	Pisa, Italy	Lithic Xerochrept[1]	EF	89-558ºC	7d	WS1 (WSI)	+	+
Giovannini et al. 1987	Sardinia, Italy	Lithic Xerochrept[1]	EF	n.d.	2-3y	WS1 (WSI)	n.d.	=
Guerrero et al. 2001	SE Spain	Calcic Rhodoxeralf[1]	LB	200-600ºC	0d	RS1	n.d.	+
Ibañez et al. 1983	Madrid (Spain)	Sandy loam	WF	n.d	335d	WS2	n.d.	+
Jordán et al. 2011	Mexico	Andosol[2]	WF	High	7-15d	CND	n.d.	-
Jordán et al. 2011	Mexico	Andosol[2]	WF	Low	7-15d	CND	n.d.	=
Josa et al. 1994	NE Spain	Typic Xerochrept[1]	EF	300ºC	8-371d	WS2, CND	=	+
Josa et al. 1994	NE Spain	Typic Xerochrept[1]	LB	50-300ºC 30 min	0d	WS2, CND	-	=
Kavdir et al. 2005	Turkey	Orthents[1]	WF	n.d.	15d	WS1	n.d.	=
Kavdir et al. 2005	Turkey	Orthents[1]	WF	n.d.	2-8y	WS1	n.d.	-
Kavdir et al. 2005	Turkey	Orthents[1]	WF	n.d.	12y	WS1	n.d.	=
Llovet et al. 2008	SE Spain	Calcaric Cambisol[2]	LB	Low-high	0d	RS1	n.d.	=
Llovet et al. 2009	SE Spain	Calcaric Cambisol[2]	WF	High	30d	RS1	-	+
Marcos et al. 2007	NW Spain	Humic Cambisol[2]	LB	100-200ºC 5-60 min	0d	WS1 (WSI)	n.d.	=
Marcos et al. 2007	NW Spain	Humic Cambisol[2]	LB	200-500ºC	0d	WS1 (WSI)	n.d.	-
Mataix-Solera & Doerr 2004	SE Spain	Xerorthent[1]	WF	Low-high	1-3y	RS1	n.d.	+
Mataix-Solera 1999	SE Spain	Typic Calcixeroll[1]	EF	Medium	1-330d	RS1	n.d.	=
Mataix-Solera et al. 2002a	SE Spain	Typic Xerorthent[1]	WF (crown)	Low	180-540d	RS1	=	+
Mataix-Solera et al. 2002a	SE Spain	Typic Calcixeroll[1]	WF (crown)	Low	180-540d	RS1	=	=
Mataix-Solera et al. 2002a	SE Spain	Typic Calcixeroll[1]	WF (surface)	High	180-540d	RS1	-	=
Mataix-Solera et al. 2008	SE Spain	Lithic Xerorthent[1]	WF	High	15m	RS1	n.d.	=
Mataix-Solera et al. 2008	SE Spain	Lithic Xerorthent[1]	WF	High	19y	RS1	n.d.	-
O'Dea 2007	Arizona (USA)	Ustic Haplargid[1]	PF	Low	4m	WS1	n.d.	=
O'Dea 2007	Arizona (USA)	Ustic Haplargid[1]	PF	Low	16m	WS1	n.d.	-
Providoli et al. 2002	S Switzerland	Typic Haplumbrept[1]	WF (surface)	High	180d	WS1	-	=
Soto et al. 1991	NW Spain	Humic Cambisols[2]	LB	170ºC	0d	RS2	=	+
Soto et al. 1991	NW Spain	Humic Cambisols[2]	LB	380-700ºC	0d	RS2	-	-
Terefe et al. 2008	Spain	Rhodoxeralfs, Palexeralfs, Calcixerepts and Palehumults[1]	LB	100-200ºC 1h	0d	WS1	n.d.	+
Terefe et al. 2008	Spain	Rhodoxeralfs, Palexeralfs, Calcixerepts and Palehumults[1]	LB	300-500ºC 1h	0d	WS1	n.d.	-
Ternan & Neller 1999	Hong Kong, China	Acrisols[2]	WF	Low-high	4-9y	RS3	n.d.	=
Úbeda & Bernia 2005	NE Spain	Lithic Xerochrept[1]	WF	Low-High	0d	CND, TDI	n.d.	+
Úbeda & Bernia 2005	NE Spain	Lithic Xerochrept[1]	WF	Low-High	240d	CND, TDI	n.d.	-
Úbeda & Bernia 2005	NE Spain	Lithic Xerochrept[1]	WF	Low-High	976d	CND, TDI	n.d.	+
Úbeda 1999	NE Spain	Lithic Xerochrept[1]	LB	200-800ºC	0d	CND, TDI	n.d.	+
Úbeda et al. 1990	NE Spain	n.d.	EF	300ºC	0d	CND, TDI, US, Emerson	n.d.	-
Valzano et al. 1997	SE Australia	Xeralf[1]	PF	Low	2d	WS1	n.d.	=
Varela et al. 2010	NW Spain	Different types	WF (28 sites)	n.d.	<30d	CND	18(-) 7(+) 3(=)	11(-) 11(+) 6(=)
Virto et al. 2007	Navarre, NE Spain	Calcic Haploxerept[1]	PF	Low	6m (burnt once per year)	WS3	=	=
Zavala et al. 2010	SW Spain, SE Australia and central Mexico	Regosols and Leptosols[2]	LB	100-150ºC 45 min	0d	CND	n.d.	=
Zavala et al. 2010	SW Spain, SE Australia and central Mexico	Regosols and Leptosols[2]	LB	250-450ºC	0d	CND	n.d.	-

[a] (1) USDA Classification (Soil Survey Staff, different versions of Keys to Soil Taxonomy 1976 – 2006), (2) WRB Classification (FAO, 2006)
[b] WF: Wildfire, LB: Laboratory burning, EF: Experimental fire (field), PF: Prescribed fire (low intensity)
[c] An arbitrary classification of fire severity interpreted from author's own descriptions
[d] Time between burning and measurements/monitoring in days. In the cases that indicate intervals it means a monitoring period. d: days, m: months, y: years
[e] RS1: Rainfall simulator method 1 (Roldán et al., 1994), RS2: Rainfall simulator method 2 (Soto et al., 1991), RS3: Rainfall simulator method 3 (Ternan et al., 1996), CND: Counting Number of Drops test (Low, 1954), TDI: Ten Drop Impact test, WS1: Wet Sieving 1 (Kemper and Rosenau, 1982), WS2: Wet Sieving 2 (Hénin y Feodoroff, 1958), WS3: Wet Sieving 3 (Le Bissonnais,1996), WSI: Water Stability Index (Giovannini and Sequi, 1976). US: Ultrasounds, WI: Water Immersion (Herrick et al., 2001)
[f] (-) size of aggregates is less in burnt than unburnt, (+): size of aggregates is higher in burnt than unburnt, (=): size of aggregates did not statistically differ between burnt and unburnt
[g] (-) aggregate stability is less in burnt than unburnt, (+): aggregate stability is higher in burnt than unburnt, (=): aggregate stability did not statistically differ between burnt and unburnt
[e] n.d.: no data available

Because of the complexity of the different possible effects and reasons for the potential changes in the fire-affected soil aggregates, the inclusion of other parameters in the studies is necessary to understand the results. The suggested parameters to include in the examination of AS are: soil organic matter, microbial biomass, water repellency, texture, aggregate size distribution, together with accurate ways of estimating fire severity. More research is needed on what implications have for soil system functioning the changes suffered by aggregates after fire. Studies including measurements at very different scales: from AS measurements in the laboratory to erosion rates measured at pedon, slope and catchment scales are also necessary.

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The complete work can be consulted at: Mataix-Solera, J., Cerdà. A., Arcenegui, V., Jordán, A., Zavala, L.M. ,2011. Fire effects on soil aggregation: A review. Earth-Science Reviews 109: 44-60.

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