

Title : Mineralogical transformations resulting from forest fire in the montane grassland systems of Southern Western Ghats, India

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1 **ABSTRACT**

2 Forest systems in the Western Ghats region have undergone significant transformations over the
3 past century and wild fires are considered as a major factor for such modifications. Apart from
4 natural fires, prescribed fire is also adopted as a management strategy in some of the forest types
5 in the region. The present study evaluated the impact of prescribed fires on soil components in
6 the high altitude montane grassland systems of southern part of the Western Ghats. Fire induced
7 mineral transformations were assessed using X- ray diffraction (XRD), thermogravimetry
8 (TGA), differential thermogravimetry (DTA), differential scanning calorimetry (DSC) and
9 thermodynamic parameters. Organic carbon content which determines key soil functions was
10 found to reduce from 1.96% before fire and stabilize at 1.48% in soils following fire. XRD and
11 TGA – DTA analyses indicated that major changes in soil during fire occur between 70° - 110
12 °C, 250° - 320 °C, and 430° - 500 °C corresponding to loss of interlayer water from phyllosilicate
13 minerals, modifications of gibbsite to amorphous minerals and goethite to hematite, and
14 transformations of kaolinite to metakaolinite, respectively. Thermodynamic parameters (ΔH , ΔS
15 and ΔG) estimated from the DSC curves show that such transformations have a positive enthalpy
16 (ΔH) and Gibbs free energy change (ΔG) values; hence are not by themselves spontaneous or
17 reversible.

18 Key words: clay minerals, XRD, TGA - DTA, DSC, thermodynamics

19 **Introduction**

20 Forests in the humid tropical regions are highly vulnerable to wildfires and such fire induced
21 changes are considered an important part of the landscape dynamics¹. Besides natural fires,
22 carefully planned, prescribed fires are also adopted in some forest systems as an important
23 management strategy to counter the spread of high intensity fires², prepare sites for planting or

24 seeding of forest species, control competing vegetation³, control pests⁴, improve habitat quality
25 needed for wildlife, increase forest stand accessibility and preserve plant species that are
26 dependent on fire. During fire, along with burning of vegetation and litter layers, the top soil
27 layers also get heated by the combined effects of combustion and heat transfer⁵. Such sharp
28 temperature gradients in the surface soil layers lead to changes in biological, physical, chemical
29 and mineralogical properties of soils⁶ and the extent of such effects depends on the type of fire
30 (intensity and duration), land slope and post-fire weather conditions⁷⁻⁸. In the humid tropical
31 region, higher fire frequency and intense precipitation pose a potential risk of increasing nutrient
32 loss and reducing soil fertility by erosion, thereby limiting recovery of soil health⁹⁻¹⁰.

33 Combustion of vegetation produces intense heat, sufficient to alter or completely change soil
34 minerals and organic matter. Conditions during fires may be suitable for decomposition,
35 dehydration, or collapse of soil minerals that play a vital role in soil processes and functions. For
36 eg: fire temperatures above 200 °C alter goethite, a very common soil mineral, to hematite or
37 maghemite. Soils in the humid tropics have abundance of kaolin which is thermally decomposed
38 around 420°C to 550 °C, producing amorphous aluminosilicates thereby having a negative
39 impact on the 1:1 clay minerals¹¹. Expanding phyllosilicates like montmorillonite are reported
40 to irreversibly change or get thermally decomposed at high temperatures¹². Dehydroxylation of
41 2:1 octahedral and interlayer hydroxide sheets may lead to decomposition of minerals such as
42 chlorite and chlorite-vermiculite¹³. Other aluminosilicate minerals, such as illites and
43 vermiculite, may also be impacted by high-intensity fire, either due to dehydration of interlayer
44 cations or as a result of release of ions such as Ca²⁺ and Mg²⁺, leading to a reduction in their 001
45 d-spacing. Reports indicate that such mineral alterations and transformations in the soil,

46 following forest fires will persist over longer periods of time¹¹. Though fires are frequent and
47 widespread in the forest systems of India, their impacts on the soil have scarcely been studied.

48 Montane grasslands, lying at an altitude of 2000 - 2600 m above mean sea level, are specific
49 systems of southern part of Western Ghats predominated by grasses along with a mix of
50 herbaceous and shrubby plants. Representative grassland systems for the study were selected at
51 Eravikulam National Park, Idukki. The area sustains the largest population of the endangered
52 ungulate, Nilgiri Tahr (*Hemitragus hylocrius*, *Ogliby*), endemic to south India. Fire is regularly
53 set as a prescribed management strategy in this ecosystem to induce fresh grass sprouts for
54 Nilgiri Tahr, and as a fire break to prevent spread of wild fire in the forests during summer.
55 Though a multitude of benefits of wild fires on the forest ecosystem has been assessed, their
56 effects on soil have rarely been evaluated in these systems.

57 In the southern part of Western Ghats' montane rain forest ecoregion, soils undergo
58 intense weathering and erosion under the prevailing topography and climate and therefore soils
59 become a qualitatively scarce resource. The protection of this scarce soil resource is essential
60 due for provisioning ecosystem services, hydrological cycle, carbon storage and nutrient
61 cycle¹⁴. Knowledge of soil degradation processes and their context in specific systems will help
62 us design practices focused on soil health protection.

63 **Materials and methods**

64 Eravikulam National Park is a protected area in the High Ranges of southern Western Ghats
65 (10°05'N and 10°20' N, and 77°0' and 77°10' E) . It covers an area of about 97 km². The area is
66 occupied by high grade supracrustal rocks, gneisses and granulites and has an undulating terrain
67 with an elevation of about 2000 m above the mean sea level. Soils are loamy sands belonging to

68 Typic Dystrustepts (USDA classification). Mean annual precipitation and temperature are in the
69 range 2300 to 3000 mm year⁻¹ and 13° to 27°C, respectively.

70 Prescribed fire was applied to 50 ha of the montane grasslands on 16th December 2016, as part
71 of management plan. Temperature at soil surface during the fire was measured using a portable
72 thermocouple fitted with a data logger. Surface soil samples (0-5 cm depth) were collected at 50
73 m interval at in the burned site at four points . The soil samples were thoroughly mixed to
74 obtain representative composite sample. Samples were collected from the site before fire (BF;
75 Date of collection - 14 December 2016), one,three and six months after burning (1B, 3B and 6B;
76 Dates of collection - 20th January 2017 , 26th April 2017 and 20th July 2017 respectively), to
77 assess chemical changes in the soil following fire. The study site was disturbed by pre-
78 monsoon showers (in April 2017) and south - west monsoon (in June -_ July 2017) before the
79 collection of 3B and 6B samples respectively. The collected samples were air dried, slightly
80 ground, sieved (2mm sieve) and stored at room temperatures for further analysis.

81 Soil reaction (pH) and electrical conductivity (EC) were estimated in 1:2.5 soil: water
82 suspension. Available N was estimated by alkaline permanganometry¹⁵, NH₄F+HCl extracted
83 phosphorus (available P) by colorimetry, neutral normal NH₄oAc extractable potassium
84 (available K) by flame photometry¹⁶ and oxidizable organic carbon content by wet oxidation
85 method¹⁷.

86 Mineralogical analyses, thermogravimetric and differential scanning calorimetric analyses were
87 carried out in BF and 1B samples only as 3B and 6B samples could have rain induced artefacts.

88 XRD analyses were done after treatment of the sample with hydrogen peroxide and sodium
89 citrate–bicarbonate–dithionite to remove organic matter and iron oxides respectively¹⁸. Silt (0.02
90 – 0.002 mm) and total clay (<0.002 mm) fractions were extracted from the soils by

91 centrifugation and randomly oriented fractions were studied by X-ray diffraction (XRD) analysis
92 (Bruker AXS D8 Advance make) with Ni-filter, Cu-K α radiation at a scanning speed of 2⁰
93 2 θ /min. Identification of the minerals in the silt and clay fractions was done as per the criteria
94 laid down by Jackson (1979)¹⁸. Thermogravimetric analysis of the soil sample was performed
95 using Perkin Elmer, Diamond TGA/DTA Analyser in the temperature range from ambient to
96 +800°C.

97 Heat induced transformations of the samples were studied by Differential Scanning
98 Calorimetry(DSC) using Mettler Toledo DSC 822e in the temperature range- -130 °C to 450°
99 C. Thermodynamic parameters such as change in enthalpy (ΔH), entropy (ΔS) and Gibbs free
100 energy (ΔG) were calculated from the DSC curves using modified Gibbs-Helmoltz equation¹⁹::

$$\Delta G^{\circ} (T) = \Delta H^{\circ}_m [1 - (T/T_m)] + \Delta C_p [(T - T_m) - T \ln (T/T_m)] \quad \text{Eq.1}$$

$$\Delta H^{\circ} (T) = \Delta H^{\circ}_m + \Delta C_p (T - T_m) \quad \text{Eq.2}$$

$$\Delta S^{\circ} (T) = \Delta S^{\circ}_m + \Delta C_p \ln (T/T_m) \quad \text{Eq.3}$$

101 where T = temperature of interest, T_m = transition midpoint temperature (midpoint of transition
102 peak in DSC curve), ΔG° = standard free energy change or the difference in Gibbs energy
103 between different states (the reactant and product); ΔH° = enthalpy change at a temperature at
104 which ΔG° is evaluated; ΔS° = entropy change at a temperature at which ΔG° is evaluated; ΔH°_m
105 = transition enthalpy change (transition peak area in DSC curve); ΔC_p = heat capacity change
106 (shift in the baseline of DSC curve)

107 **Results and discussions**

108 **Fire induced chemical changes in the grassland soils**

109 Soil pH and EC was found to be substantially modified by fire. They increased from 5.76 to 5.81
110 and from 0.14 dS/m to 0.38 dS/m respectively (Table 1). The increase in soil reaction (pH) is an

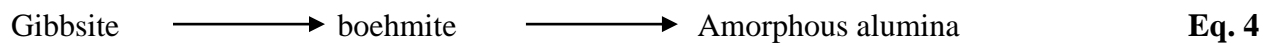
111 indication of improvement of alkali cations in soil released from oxidised organic matter²⁰.
112 Burning of organic residues in soils and plant litter produces soluble salts of Ca and K, thereby
113 increasing EC²¹. However, the poorly ordered acid forming soluble forms of Fe and Al minerals
114 formed by dehydroxylation (discussed later) of the parent crystalline minerals during fire
115 neutralizes the bases and even reduces the pH compared to the original in the long run. Leaching
116 of bases during rains further reduces the soil pH. Organic carbon, an important indicator of soil
117 health decreased following fire substantially from 1.98% (in BF) to 1.46% (in 6B). A combined
118 effect of fire induced carbon oxidation and humic acid transformation effectively reduces the
119 oxidizable and labile carbon forms in soil⁷. Carbon being the energy source for microbial
120 activities, such decline in organic carbon pool will seriously affect the soil food web and thereby
121 soil processes and functions, leading to its rapid degradation.

122 In unburned soils, the silt fraction was found to be dominated by illite, kaolinites, goethite,
123 quartz and gibbsite while the clay fraction had predominance of kaolinite, illite, gibbsite and
124 kaolinite - hydroxy-interlayered vermiculite (hereafter mixed layer aluminosilicate minerals) (Fig
125 1 and 2). In a humid tropical climate and under an acid weathering environment, formation of 1:1
126 type minerals (eg: kaolinite), hydroxy-aluminium interlayering and interstratifications of 2 : 1
127 and 1:1 layers to form mixed layer aluminosilicate minerals is a primary reaction. The results
128 indicate that fire affects the nature of these soil minerals and presumably their interaction with
129 nutrients. TGA - DTA curves show that major transformations of soil occur in the temperature
130 range 70 - 110 °C, 250 - 320 °C and 430 - 500 °C (Fig. 3a-b).

131 **Fire induced mineralogical changes in the grassland soils**

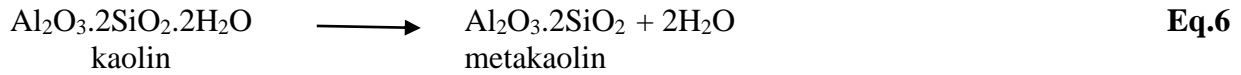
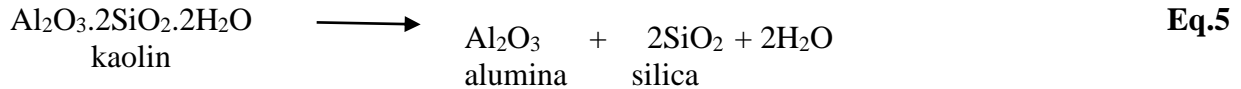
132 . Following the fire, the mineralogical composition of silt fraction changed to metakaolinite,
133 calcite, haematite and quartz. Disappearance of mixed layer aluminosilicate minerals, illites and
134 appearance of peaks representing amorphous gibbsite, calcite and haematites were the dominant
135 changes in the clay fraction. The results indicate that fire affects the nature of soil minerals and
136 presumably their interaction with soil nutrients.

137 Soils in the humid tropics are usually dominated by kaolinites, and sesquioxide minerals²².
138 However, forest soils in the region are relatively young and have abundance of mica group
139 minerals and mixed layer aluminosilicates along with kaolinites²³. Under high temperatures
140 induced by fire, dehydroxylation and recrystallization occur in a step wise manner leading to the
141 alteration of minerals in both silt and clay fractions²⁴. Earlier studies have reported that heating
142 temperatures of about 200 °C cause dehydration and alter gibbsite to complex crystalline and
143 amorphous alumina mineral assemblages^{25 -26}



144 At 300 °C, goethite alters to partly ordered hematite²⁷. The presence of goethite in the samples
145 before fire and their relatively lower XRD peak intensities or absence in the burnt samples
146 confirms the earlier studies that a good portion of goethite gets converted to haematite under
147 high temperature conditions due to fire. Hematite formation from goethite following fire may
148 be by way of dehydroxylation of the crystalline goethite or dissolution of goethite and
149 reprecipitation through an intermediate phase such as hydrohematite in soil solution²⁸.

150 The temperature due to fire in the study site was recorded to rise up to 800 °C with a
151 mean temperature of 450° - 600 °C. Such intense temperatures above 600 °C provide sufficient
152 energy to modify kaolin to a mixture of independent amorphous alumina and amorphous
153 silica or metakaolin²⁹:



154 Calcite, another major mineral phase that developed in the soil after burning is attributed to the
 155 transformation of calcium oxides in the vegetative tissue following incineration³⁰⁻³¹. The loss
 156 of crystalline 2:1 minerals such as mixed layer aluminosilicate minerals and illites from the clay
 157 fractions during fire may seriously impair the ecosystem functions of soil as these expanding
 158 clay minerals provide a wide range of services from nutrient buffering to cation exchange
 159 capacity of soils.

160 **Fire induced thermo gravimetric changes in grassland soils**

161 During fire, the first chemical reaction was found to occur around 70° - 110 °C, which can be
 162 attributed to the loss of interlayer water molecules from 2:1 type minerals (illites or mixed layer
 163 aluminosilicate clay minerals) and is an endothermic process. The interlayer water in 2:1 layer
 164 minerals can be either "bound water" or "unbound water", a significant portion of which gets
 165 removed at ~ 110 °C³². The second endothermic peak was observed in the temperature range of
 166 250 °C - 320 °C corresponding to dehydroxylation of goethite to form hematite. Transformation
 167 of gibbsite to amorphous alumina and complete oxidation of soil organic matter also occur
 168 around this temperature range. Kaolinite transformation to metakaolinite occurring at ~ 550 °C
 169 is represented by the third endothermic peak in the TGA spectrum. Maximum weight
 170 loss was found in the temperature range 250 to 320 °C corresponding to three major
 171 transformation processes (gibbsite to amorphous silica , goethite to hematite , oxidation of
 172 organic matter) and minimum during kaolinite to metakaolinite transformation. Kaolinite being

173 low activity non-expanding clay holds less water and cations (K^+ , Ca^{2+} , Mg^{2+}) in its lattice and
174 higher temperature is required to disrupt the structure leading to its transformation.
175 . TGA spectra indicated that unburned soil samples lost 16.89 % of their weight when heated
176 in a temperature range of ambient to 800 °C (Table 2). These values are close to the
177 theoretical dehydroxylation related weight loss value for kaolinite (value of 14 %) at 520 °
178 C³⁴. On the other hand, TGA spectra of burned soils had a weight loss that was 43.5 percent
179 lesser than the unburned soil in the same temperature range. The higher weight loss in the
180 TGA spectra of unburned samples than burned soils can be attributed to the loss of strongly
181 mineral adsorbed water in the former between 110 °C and 400 °C³³. In the present study,
182 soils had reached temperatures up to ~800 °C during fire that is sufficient enough to cause
183 dehydroxylation and loss of water and volatile components³⁴ ..

184 **Thermodynamics of fire affected soil transformations**

185 Three endothermic peaks have been observed in the DSC curve corresponding to
186 the transformations that are obvious in the TGA – DTA spectra. The endothermic peaks in
187 DSC spectra, between 49.54 – 139.91 °C, 262.7 – 289.79 °C and 442.49 – 497.73 °C,
188 correspond to the weight loss points in TGA and confirm dehydroxylation and
189 recrystallization processes in soil (Fig 4a–b). The characteristic midpoint transition
190 temperatures (T_m) for transition or transformation during burning was found to be
191 85.20 °C, 278.70 °C and 473.88 °C corresponding to the loss of interlayer water,
192 dehydroxylation reactions and metakaolinite formation respectively (discussed earlier).
193 Burned soil (1B) already deprived of most of the components though gave peaks at these
194 temperatures, showed DSC peak intensities lower than in the unburned soils. The Gibbs free
195 energy values were found to be maximum at 85.20 °C in both BF and 1B, corresponding to
release of hygroscopic moisture from the soil. . The positive

196 values for free energy (ΔG) and enthalpy (ΔH) and negative entropy (ΔS) for the soil mineral
197 transition or transformation processes show that these reactions are non-spontaneous and
198 irreversible in soil. Under natural conditions these processes occur at infinitesimally small rate
199 and take millions of year to complete. However, fire imparts large amount of energy into the soil
200 system and witnesses irreversible transformation of mineral phases within a short span of
201 time (positive Gibbs free energy values). It can be concluded that frequent fires at the same
202 location will accumulate transformed minerals like metakaolin and inert resistant minerals like
203 hematites (minerals at the end of a weathering sequence) and drastically deplete the soil health.

204 **Conclusions**

205 Influence of fire on the soil system depends on its severity. The soils in the montane grassland
206 systems show temporary nutrient enrichment after burning, but revert to a lower content than the
207 original contents within a short span of six months. During fire, major changes were found to
208 occur between 70° - 110 °C, 250 ° - 320 °C and 430 ° - 500 °C. Between 70 ° and 110 °C
209 phyllosilicate minerals lost water molecules through an endothermic process. Major
210 transformations were found to occur around 250 ° - 320 °C which include transformation of
211 gibbsite to amorphous minerals, goethite to hematite and oxidation of organic matter producing
212 substantial weight loss in the samples. Kaolinite, a major soil mineral in the tropical soils, was
213 altered between ~ 430° - 500 °C to metakaolinite during fire. Thermodynamic parameters
214 estimated from DSC curves indicate that these soil modifications have positive ΔH and ΔG
215 values and hence are not, by themselves, feasible or reversible under natural conditions. The
216 large amount of heat energy infused by fire accelerated the processes which would have
217 otherwise occurred at an infinitesimally slow pace under natural conditions. Hence, continuous
218 use of fire as a management strategy will reduce active organic fractions and accumulate

219 transformed minerals like amorphous alumina, haematite and metakaolins in the pristine
220 ecosystems of southern part of Western Ghats within a short period, thereby depleting the soil of
221 its natural composition and its capacity to support ecosystem services.

222 **References**

- 223 1. Pausas, J.G. and Keeley, J.E., A burning story: the role of fire in the history of life.
224 *Bioscience*, 2009, **59**, 593–601.
- 225 2. Bento-Gonçalves, A., Vieira, A., Úbeda, X. and Martin, D., Fire and soils: key concepts and
226 recent advances. *Geoderma*, 2012, **191**, 3–13.
- 227 3. Brooks, M. and Lusk, M., Fire Management and Invasive Plants: A Handbook. United States
228 Fish and Wildlife Service, Arlington Virginia, 2009, 27 pp.
- 229 4. Parker, T.J., Karen, M.C. and Mathiasen, R.L., Interactions among fire, insects and
230 pathogens in coniferous forests of the interior western United States and Canada. *Agric. For.*
231 *Entomol.*, 2006, **8**, 167–189.
- 232 5. Certini, G., Effects of fire on properties of forest soils: a review. *Oecologia*, 2005, **143**, 1–10.
- 233 6. Hubbert, K.R., Preisler, H.K., Wohlgemuth, P.M., Graham, R.C. and Narog, M.G.,
234 Prescribed burning effects on soil physical properties and soil water repellency in a steep
235 chaparral watershed, southern California, USA. *Geoderma*, 2006, **130**, 284–298.
- 236 7. González-Pérez, J.A., González-Vila, F.J., Almendros, G. and Knicker, H., The effect of fire
237 on soil organic matter—a review. *Environ. Int.* 2004, **30**, 855–870.

- 238 8. Francos, M., Pereira, P., Alcañiz, M., Mataix-Solera, J. and Úbeda, X., Impact of an intense
239 rainfall event on soil properties following a wildfire in a Mediterranean environment (North-
240 East Spain). *Sci. Total Environ.*, 2016, **572**, 1353–1362.
- 241 9. Thomas, A.D., Walsh, R.P.D. and Shakesby, R.A., Nutrient losses in eroded sediment after
242 fire in eucalyptus and pine forests in the Mediterranean environment of northern Portugal.
243 *Catena* , 1999, **36**, 283–302.
- 244 10. Shakesby, R.A., Post-wildfire soil erosion in the Mediterranean: review and future research
245 directions. *Earth Sci. Rev.*, 2011, **105**, 71–100.
- 246 11. Ulery, A.L., Graham, R.C. and Bowen, L.H. Forest fire effects on soil phyllosilicates in
247 California. *Soil Sci. Soc. Am. J.*, 1996, **60**, 309–315.
- 248 12. Sarikaya, Y., Önal, M., Baran, B., Alemdaroğlu, T., The effect of thermal treatment on some
249 of the physicochemical properties of a bentonite. *Clay Clay Miner.*, 2000, **48**, 557–562.
- 250 13. Sertsu, S. H. and Sanchez, P. A. Effects of heating on some changes in soil properties in
251 relation to an Ethiopian land management practice, *Soil Sci Soc Am J.*, 1978, **42**, 940–944.
- 252 14. Fonseca, F., De Figueiredo, T., Nogueira, C. and Queirós, A., Effect of prescribed fire on
253 soil properties and soil erosion in a Mediterranean mountain area. *Geoderma*, 2017, 307,
254 172–180.
- 255 15. Subbiah, B.V. and Asija, G.L., A rapid procedure for the determination of available nitrogen
256 in soils. *Curr. Sci.*, 1956, **25**, 259 - 260.

- 257 **16.** Jackson, M.L., Soil chemical analysis. Prentice Hall Inc., Englewood cliffs, New Jersey,
258 1958, pp 498.
- 259 17. Walkley, A. and Black, I. A., An examination of the Degtjareff method for determining soil
260 organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.*,
261 1934, **37**, 29–38.
- 262 18. Jackson, M. L., Soil Chemical Analysis – Advanced Course, University of Wisconsin,
263 Madison, WI, 1979.
- 264 19. Bruylants, G., Wouters, J. and Michaux , C., Differential Scanning Calorimetry in Life
265 Science: Thermodynamics, Stability, Molecular Recognition and Application in Drug
266 Design. *Curr. Med.Chem.*, 2005, **12**, 2011-2020.
- 267 20. Terefe, T., Mariscal-Sancho, I., Peregrina, F. and Espejo, R., Influence of heating on various
268 properties of six Mediterranean soils. A laboratory study. *Geoderma*, 2008, **143(3)**:273-280.
- 269 21. Úbeda, X. and Outeiro, L., Physical and chemical effects of fire on soil. In: Cerdà, A.,
270 Robichaud, P.R. (Eds.), *Fire Effects on Soils and Restoration Strategies*. Science Publishers,
271 Enfield, NH, 2009, pp. 105–133.
- 272 22. Chandran, P., Ray, S. K., Bhattacharyya, T., Srivastava, P., Krishnan, P. and Pal, D. K.,
273 Lateritic soils of Kerala, India: their mineralogy, genesis, and taxonomy. *Aust. J. Soil Res.*,
274 2005, **43**, 839–852.
- 275 23. Sandeep, S. and Sujatha, M. P., Mineralogy of kaolin clays in different forest ecosystems of
276 southern Western Ghats, India. *Curr. Sci.*, 2014, *107*, 875 -881.

- 277 24. Ketterings, Q.M., Bigham, J.M. and Laperche, V., Changes in soil mineralogy and texture
278 caused by slash-and-burn fires in Sumatra, Indonesia, *Soil Sci. Soc., Am. J.*, 2000, **64**, 1108–
279 1117.
- 280 25. Bokhimi, X., Sanchez-Valente, J. and Pedraza, F., Crystallization of sel-gel boehmite via
281 hydrothermal annealing. *J. Solid State Chem.* 2002, 166, 182-190.
- 282 26. Wang, H., Xu, B., Smith, P., Davies, M., Desilva, L. and Wingate, C., Kinetic modeling of
283 gibbsite dehydration/amorphization in the temperature range 823-923K. *J. Phys. Chem.*
284 *Solid.* 2006, **67**, 2567-2582.
- 285 27. Cornell, R.M. and Schwertmann, U., The iron oxides: Structure, properties, reactions,
286 occurrence and uses. Berlin, VCH Weinheim, 1996, 573 p.
- 287 28. Fan, H., Song, B. and Li, Q., Thermal behavior of goethite during transformation to
288 hematite. *Mater. Chem. Phys.*, 2006, **98**, 148-153.
- 289 29. Mitra, G.B and Bhattacharjee, C., X - ray diffraction studies on the transformation of
290 kaolinite into metkaolin: I.Variability of interlayer spacings. *Am. mineral.*, 1969, **54**, 1409 -
291 1418.
- 292 30. Iglesias, T., Cala, V. and Gonzalez, J., Mineralogical and chemical modifications in soils
293 affected by a forest fire in Mediterranean area. *Sci. Total Environ.* 1997, **204**, 89 - 96.
- 294 31. Badía, D. and Marti, C., Plant ash and heat intensity effects on chemical and physical
295 properties of two contrasting soils. *Arid Land Res. Manage.*, 2003, 17, 23-41.

296 32. Walker, G. F., Vermiculites and some related mixed layer minerals, x - ray identification of
297 crystal structures of clay minerals, Monograph, The Mineralogical Society of London,
298 1951.

299 33. Ptáček, P., Kubátova, D., Havlica, J., Brandštetr, J., Šoukal, F. and Opravil, T., Isothermal
300 kinetic analysis of the thermal decomposition of kaolinite: The thermogravimetric study.
301 Thermochim Acta, 2010, **501**, 24-29.

302 34. Tan, K.H., and Hajek, B.F., Thermal analysis of soils. In: R.C. Dinauer (Ed.), Minerals in
303 Soil Environments, SSSA, Madison, Wisconsin, USA, 1977, pp. 865- 884.

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Table 1. Effect of fire on selected chemical properties of soil in the montane grassland system of Southern Part of Western Ghats				
Parameters	BF	1B	3B	6B
pH	5.76	6.17	5.73	5.65
EC	0.14	0.65	0.26	0.18
Organic carbon (%)	1.98	1.48	1.42	1.46
Available N (kg/ha)	326.00	338.00	328.00	324.00
Available P (kg/ha)	24.97	32.25	28.42	26.71
Available K (kg/ha)	328.27	635.41	390.36	357.92
BF - before fire; 1B - one month after burning, 3B - three months after burning; 6B - six months after burning				

Table 2. Effect of fire on thermogravimetric and thermodynamic properties of montane grassland soils in the Southern Western Ghats						
Sample	Weight loss (%)	DTG peak		Thermodynamic Parameters		
		Temp (°C)	Rate of decomposition (mg/min)	ΔH (J/g)	ΔS (10^{-5} J/K)	ΔG (J/g)
BF	16.89	85.19	0.18	65.67	-1.25	65.67
		275.97	0.24	9.13	-0.47	9.13
		455.67	0.11	15.00	-0.25	15.00
1B	9.58	82.23	0.09	81.10	-1.55	81.10
		275.46	0.09	4.03	-0.33	4.03
		455.27	0.08	37.28	0.67	37.27
BF - before fire; 1B - one month after burning						

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336 **Figure Legends**

337 Figure 1. XRD patterns of randomly oriented silt sized fraction of soils from montane grassland
338 systems of sothern part of Western Ghats a. silt fractions in soil before fire (BF); b.
339 silt fractions in soil after fire (IB). (C – calcite; Go – goethite; G – gibbsite; H -
340 hematite; IL - illite; K - kaolinite; MK – metakaolinite; Q – quartz)

341 Figure 2. XRD patterns of randomly oriented clay sized fractions from montane grassland
342 systems of sothern part of Western Ghats a. clay fractions in soil before fire (BF); b.
343 clay fractions in soil after fire (1B) (C – calcite; G – gibbsite; H - hematite; IL - illite;
344 K - kaolinite; ML – mixed aluminosilicate layer mineral; Q – quartz)

345 Figure 3. Fig.3: TGA –DTA curves of soil samples from montane grassland systems of Sothern
346 part of Western Ghats a. soil before fire (BF); b. soil after fire (1B).

347 Figure 4. DSC spectra of soil samples from montane grassland systems of sothern part of
348 Western Ghats a. soil before fire (BF) b. soil after fire (1B)

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Figure 1.

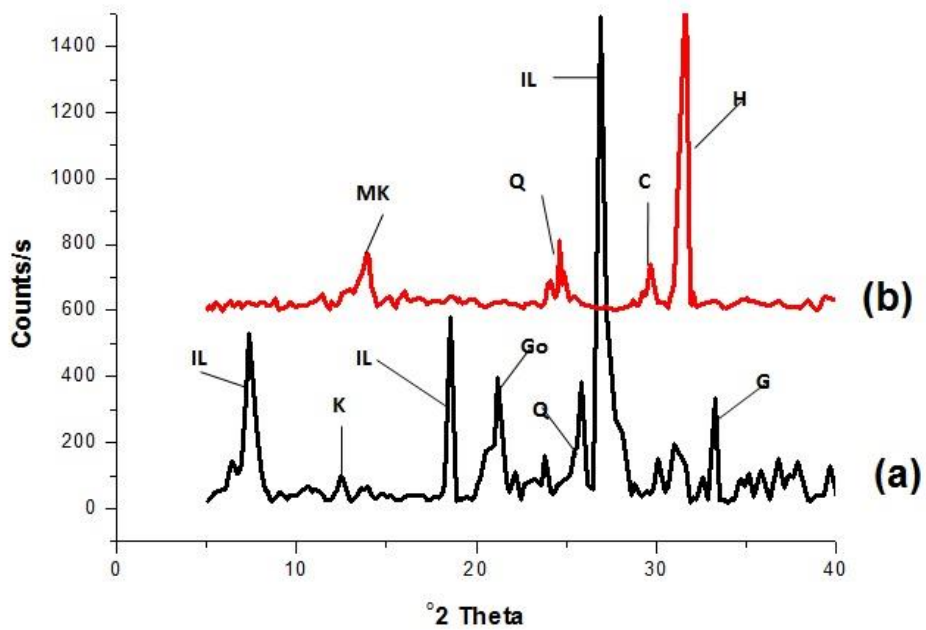


Figure 2.

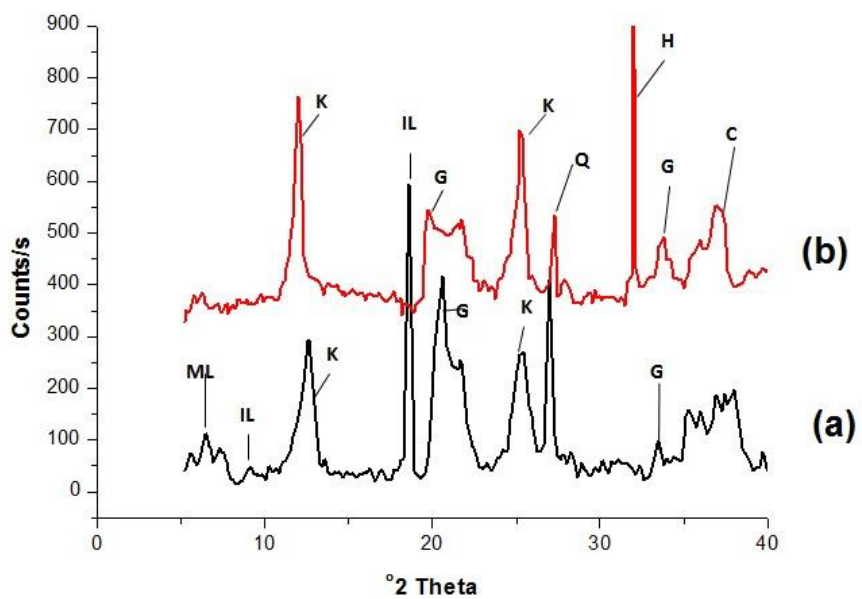


Figure 3.

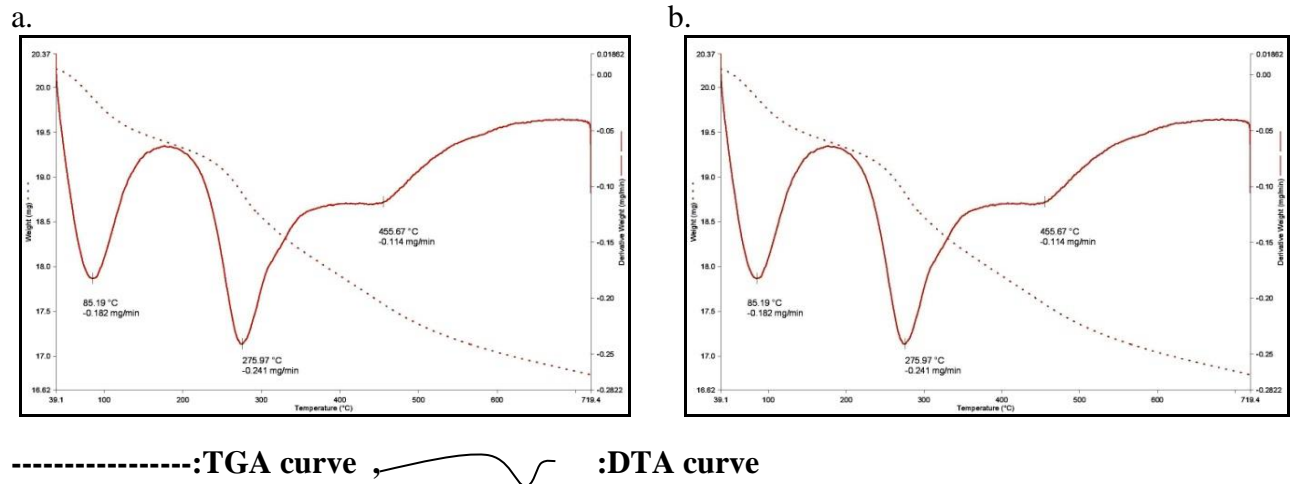


Figure 4.

