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Modelling wildfire effects on the coevolution of soils and flammable temperate forests

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Abstract

Climate drives the coevolution of vegetation and the soil that supports it. Wildfire dramatically affects many key eco-hydro-geomorphic processes, but its potential role in coevolution of soil-forest systems has been largely overlooked. The steep landscapes of southeastern Australia provide an excellent natural laboratory to study the role of fire in the coevolution of soil and forests, as they are characterized by temperate forest types, fire frequencies, and soil depths that vary systematically with aridity. The aims of this study were (i) to test the hypothesis that in Southeastern Australia, fire-related processes are critical to explain the variations in coevolved soil-forest system states across an aridity gradient and (ii) to identify the key processes and feedbacks involved. To achieve these aims, we developed a numerical model that simulates the coevolution of soil-forest systems which employ eco-hydro-geomorphic processes that are typical of the flammable forests of southeastern Australia. A stepwise model evaluation, using measurements and published data, confirms the robustness of the model to simulate eco-hydro-geomorphic processes across the aridity gradient. Simulations that included fire replicated patterns of observed soil depth and forest cover across an aridity gradient, supporting our hypothesis. The contribution of fire to coevolution increased in magnitude with aridity, mainly due to the higher fire frequency and lower post-fire infiltration capacity, increasing the rates of fire-related surface runoff and erosion. Our results show that critical feedbacks between soil depth, vegetation, and fire frequency dictate the trajectory and pace of the coevolution of flammable temperate forests and soils.

1. Introduction

Interactions and feedbacks between soil and vegetation are key factors in controlling catchment ecohydrological behavior (Donohue et al., 2007, 2012; Trancoso et al., 2016; Zhang et al., 2004). Thus, understanding how soil-vegetation systems coevolve can help explain observed variations in catchment responses and enable better predictions of change in response to future climate scenarios (Troch et al., 2015). Coevolution in this context is defined as a climatically driven process in which interactions and feedbacks between vegetation and its supporting soil causes ongoing changes in their properties (Berry et al., 2005; Porder, 2014; Troch et al., 2015; van Breemen, 1993). Due to its interdisciplinarity, complexity, and nonlinearity and because it operates outside of our observational time scales, studying the coevolution of soil-vegetation systems requires models that couple ecological, hydrological, and geomorphological processes and their drivers under one numerical framework (Istanbulluoglu, 2016).

Fire affects both vegetation and soil and is therefore likely to play a role in their coevolution. Fire changes the hydrological properties of the system by removing the canopy cover and changing the properties of the soil surface (DeBano, 2000; Inbar et al., 2014; Shakesby & Doerr, 2006), often making it more conducive to surface runoff (Nyman et al., 2010; Shakesby & Doerr, 2006) and more erodible (Noske et al., 2016; Nyman et al., 2013). These combined transient effects often result in a temporary increase in soil erosion of different magnitudes (Lane et al., 2006; Moody & Martin, 2001; Nyman et al., 2011; Prosser & Williams, 1998). Fire had also been shown to cause transient changes in the water and energy balance by altering the amount of water that infiltrates, is intercepted, and is transpired by the local forested systems (e.g., Nolan et al., 2014).

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The role of fire in coevolution had been mainly investigated through its geomorphic effect on landform change (Benda & Dunne, 1997; Gabet & Dunne, 2003; Istanbulluoglu et al., 2004; Istanbulluoglu & Bras, 2005; Orem & Pelletier, 2016; Roering & Gerber, 2005). Here we point to an important feedback that is indirectly related to the geomorphic effects of fire that might have been overlooked. Soil depth holds an important role in controlling vegetation water holding capacity at a point by setting an upper limit to the plant available water capacity (Hahm et al., 2019). This implies that fire-driven erosion processes could potentially push soil-vegetation systems toward an alternative coevolved state by affecting its soil depth, if high fire-frequency is sustained over long time scales. Accounting for the processes that affect fire frequency is therefore necessary to fully untangle the role of fire in the development of the critical zone and landscape evolution.

In the landscape evolution literature, fire is often regarded as a "disturbance" and is modeled stochastically (Gabet & Dunne, 2003; Istanbulluoglu et al., 2004; Istanbulluoglu & Bras, 2005). However, evidence shows that long-term fire frequency depends on processes that control the availability of burnable fuel (Pausas & Bradstock, 2007) and their moisture state (Pausas & Bradstock, 2007; Taufik et al., 2017), making it a dynamic process that is coupled to the ecohydrological state of soil-vegetation systems. This implies that fire is tightly coupled within coevolutionary feedbacks both as a forcing and as a response variable. The modelling of a fire regime that is coupled to the hydrological state of the modeled systems has been explored in some dynamics vegetation models (e.g., Prentice et al., 2011; Thonicke et al., 2010, 2001; Yue et al., 2014). These models, however, do not include the geomorphic effect of fire and its consequences on processes and feedbacks in the coevolution of soil-vegetation systems. The full range of mechanisms by which fire can drive landscape change and coevolution therefore remains unclear. To address this limitation, a model is required that couples fire to both ecohydrological and geomorphic processes and enables the complex coevolution of vegetation and soil to be more robustly investigated.

The central highlands in southeastern (SE) Australia provide an ideal natural laboratory to investigate the role of fire in coevolution of soil-vegetation systems for several reasons: (i) It is home to some of the most flammable forests on earth; (ii) a gradient in temperate climate had resulted in a range of forest types with different fire regime (Cheal, 2010); and (iii) the lack of active uplift (Czarnota et al., 2014; Wellman, 1987) and the lack of glaciation below 1,200melevation during late Pleistocene (Barrows et al., 2001) narrow down the drivers and possible geomorphic processes that might have affected coevolution in the area.

The aims of this study were to (i) test the hypothesis that fire-related processes are critical to explain the variations in coevolved soil-forest systems across an aridity gradient in SE Australia and (ii) to identify key processes and feedbacks involved the coevolution process. To achieve the aims, we developed a numerical model (COevOLution of FLAMmable Systems—CoolFlameS) that simulates the coevolution of soil-forest systems and is underpinned by equations that couple fundamental ecohydrological, vegetation dynamics, and geomorphological processes. CoolFlameS was formulated, parameterized, and calibrated to simulate systems that are typical to SE Australia. The model was evaluated by comparing model outputs of system properties and process rates against observations, measurements, and published data.

2. Method

In systems where nutrient availability is not limiting plant growth, vegetation carrying capacity is driven by the supply and demand for water and the ability of the critical zone to store it (Hahm et al., 2019). While water supply and demand are often affected by climate and topography (Nyman, Sherwin, et al., 2014; Rasmussen et al., 2015), the ability of a system to store water depends on soil properties, primarily depth, but also texture, porosity, and organic matter content (Clapp & Hornberger, 1978; Saxton & Rawls, 2006). CoolFlameS is therefore based on the conceptual model whereby the structure of soil-forest systems at any point in time and space is controlled by the legacy of climatically driven feedbacks between vegetation, fire, and the ability of the system to hold moisture, which is dictated by soil depth (Hahm et al., 2019). In the proposed model (Figure 1a), soil moisture plays a central role in coevolution by controlling evapotranspiration (ET) and primary productivity (Montaldo et al., 2005; Rodriguez- Iturbe, 2000) and by ecohydrological control on the flammability of the system (Krueger et al., 2016). Soil water holding capacity in the model is determined primarily by soil depth and, together with climate (i.e., aridity), limits ET and biomass accumulation (Klein et al., 2015; Milodowski et al., 2015). Fire removes vegetation and causes changes to soil hydraulic properties (Certini, 2005; DeBano, 2000), which temporarily increases erosion potential (Nyman et al., 2013; Wagenbrenner et al., 2010). By this approach, changes in climate and fire frequency can alter the depth of the soil and its water and biomass holding capacity and thereby drive coevolution.

In order to investigate the role of fire in the coevolution of soil-vegetation systems, it is necessary to couple fire with ecological, ecohydrological, and geomorphic processes. One of CoolFlameS major novelty is that it bridges the gap between landscape evolution, land surface models, and flammability through coupling ecohydrology, vegetation dynamics, and moisture deficits with geomorphic processes that control soil depth. This feature is missing from existing models. For this purpose, we employ a combination of new and well-established generic equations that represent ecohydrological, geomorphological, and forest dynamics processes as defined in existing literature. Moreover, in order to represent SE Australian systems appropriately, CoolFlameS was developed from deep ecohydrological and geomorphic understanding stemming from decades of intensive research and model development. Due to the long time scale and multitude of disciplines and processes involved in the coevolution of soil-vegetation systems, simplicity was prioritized over complexity during model development. To overcome this potential shortcoming, model components (i.e., ecohydrology, geomorphology, and fire) were evaluated by comparing simulation results with measurements and published values.

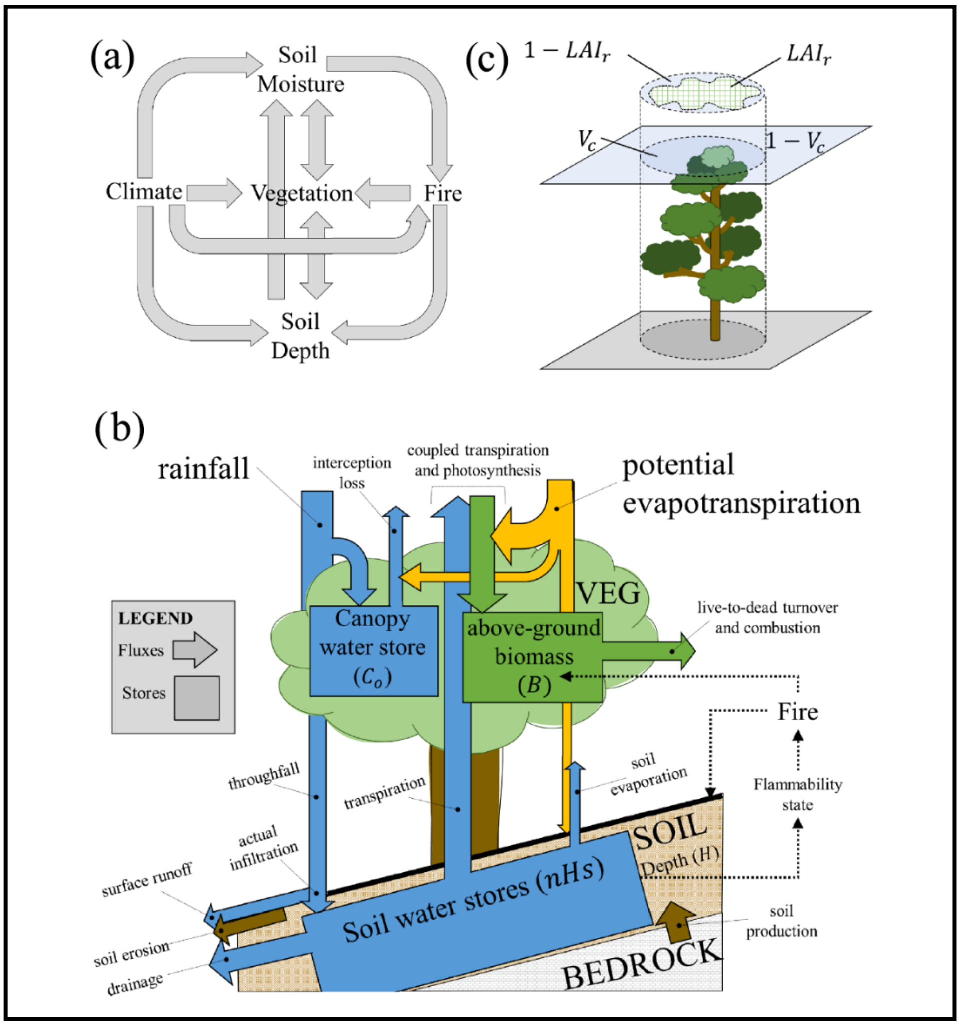

Figure 1-(a) A conceptual model that describes the coevolution of a coupled soil-vegetation system and (b) a schematic representation of what eco-hydrogeomorphic processes represented in CoolFlameS are, and the manner in which they are coupled. The dynamics of soil depth (H), soil moisture (nHs, where s is degree of saturation and n is porosity), and standing biomass (B) are expressed by a set of equations described in Inbar et al. (2020). Thick colored arrows represent fluxes of water (blue), energy (yellow), carbon (green), and minerals (brown). Thin dashed arrows point to the effects of soil moisture on fire and the effect of individual fire on forest cover and soil surface properties. An illustration of the spatial representation of the model system is presented in panel (c). The system surface area is divided horizontally into vegetated (Vc) and bare (1 − Vc) proportions. The vegetated area is further divided into covered (LAIr) and uncovered (1 − LAIr) proportions.

3. Results and Discussion

The performance of the model for the replicating observed patterns in soils, hydrology, fire and vegetation can be found in Inbar et al. (2020). A brief overview of the results and discussion is provided below.

3.1. Experiment 1—The Role of Fire in Coevolution (Evaluating the Hypothesis)

Our initial hypothesis that fire-related processes are critical to explain the variations in coevolved soil-forest system states across an aridity gradient is supported by the results (Figures 2a and 2b) showing that simulations with fire are more consistent with contemporary observation than simulations without fire. Model results show that the relative role of fire increases with aridity (Figures 2a and 2b). This can be explained by the more frequent fires and higher erosion rates as aridity increases. As aridity increases beyond the value of 1, so does the relative contribution of fluvial erosion rates, and this effect is further amplified by fire. The fact that the predicted projected canopy cover (Vc − ss) trends in a similar manner as soil depth (Hss) with respect to aridity can be explained by the change in biomass holding capacity of the soil, caused by the interaction between climate, fire, and the balance between soil production and erosion on soil depth (Hahm et al., 2019). The phenomenon that erosion controls vegetation patterns was observed by Milodowski et al. (2015) in the northern Californian Sierra Nevada, USA, where mean basin slope, a proxy of long term erosion rate, explained 32% of variance in above ground biomass, outweighing the effect of other factors, such as MAP, temperature, and lithology. The authors ascribed this effect to the reduction in water holding capacity due to the limitation dictated by thinner saprolite.

3.2. Experiment 2—The Role of Fire-Related Processes in Coevolution

Results indicates that among the three possible effects of fire that were explored, the role of post-fire reduction in Ic on Hss and Vc − ss was the largest (Figures 2c and 2d). Post-fire reduction in Ic can explain the increasing dominance of fluvial processes at aridity values >1, which result in shallower soils from simulations with fire beyond that point (Figures 2a and 2b). For aridity values <1, post-fire reduction in Ic is not sufficiently large to affect surface runoff. Consequently, on slopes supporting wet forest types, the relative role of diffusive processes is higher compared to that of fluvial processes. Post-fire erosion is often associated with loss of cover, increased hydrophobicity, and reduction in root cohesion (Istanbulluoglu & Bras, 2005). The latter process was not implemented explicitly in CoolFlameS but is implicit within the surface cohesiveness term. Our results indicate that long-term erosion is more sensitive to reduction in Ic (and consequential increase in surface runoff) than to the amount of sediment that is available to be transported after fire (−ΔCO; Figures 2e–2h). This can be explained by the interplay between the transport-limited nature of the non cohesive material and the time it is available for transport (Nyman et al., 2013).

The relative role of post-fire reduction in forest cover (−ΔLAI) was found to be lower than the two other processes examined (Figures 2). This result can be explained by the effect of the interaction between forest cover and infiltration capacity on fluvial erosion across the aridity gradient. At higher aridity values, background forest cover is always relatively low (Figure 2b), and the effect of the short-lived post-fire removal of vegetation cover on fluvial erosion is insignificant compared to the reduction in infiltration capacity during the same period. In wetter climates, vegetation density is higher and the effect of the temporary loss of cover on fluvial erosion rates can be significant. However, this effect is balanced by the high infiltration capacity, which keeps surface runoff rates low even after fire (Noske et al., 2016). These results indirectly suggest that the time to forest canopy recovery that explicitly depend on forest recovery trait has little impact on long-term coevolution of soil depth and vegetation in SE Australia.

In a study aggregating hundreds of post-fire infiltration and runoff measurements, Sheridan et al. (2015) found that post-fire runoff generation was highly correlated with aridity, such that more arid hillslopes, that often have younger and less developed soils, were associated with higher post-fire sediment yields. Our results indicate that the trend of Hss with aridity (Figure 2a) is determined mainly by the amount of surface runoff that is generated (which is controlled by the infiltration capacity) and how it affects post-fire fluvial erosion rates. Our model suggests that in a world without fire, the differences in soil depth and vegetation cover between dry and wet systems would have been significantly smaller to what is currently observed (Figures 2a and 2b). Other theoretical experiments had shown a significant increase in forest cover on the expense of grasslands in a world without fire (Bond et al., 2005). Our results highlight the possible role of fire-related changes in soil depth on global distribution of vegetation.

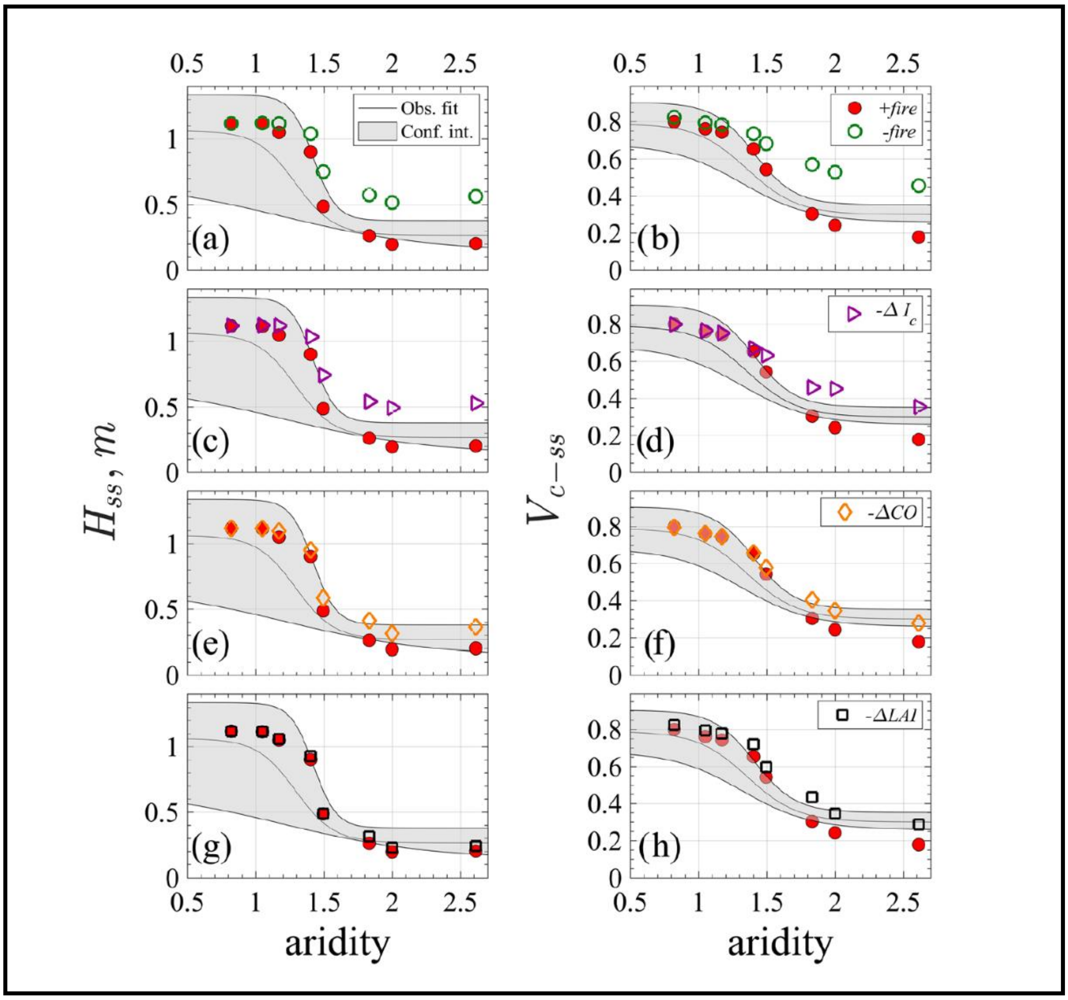

Figure 2-Modeled (Hss and Vc − ss) and observed soil depth and projected vegetation cover as a function of aridity for (a and b) simulations with (+fire) and without fire (−fire) and for simulations with fire but without post-fire changes in (c and d) infiltration capacity (−ΔIc); (e and f) soil cohesiveness (−ΔCO); and (g and h) canopy cover (−ΔLAI). The figure presents results for Experiments 1 (a and b) and 2 (c–h). Hss and Vc − ss values are plotted over functions and 95% confidence interval (gray area) fitted to soil depth measurements (Inbar et al., 2018) and remotely sensed vegetation cover using annual LANDSAT values (Tern AusCover, 2017) for areas near the three steepest sites (Table S5). Confidence interval for vegetation cover was generated for 1,000 randomly sampled values of remotely sensed vegetation cover.

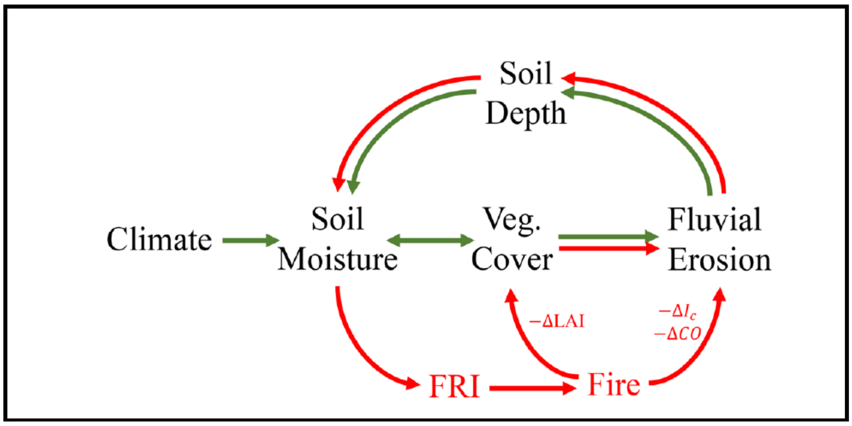

Figure 3-Climatically driven feedback between soil moisture, fire return interval (FRI), fluvial erosion, and soil depth. Red arrows represent effects that are related to fire and green arrows those that are not. In this feedback, long term change in climate affects soil moisture, vegetation cover, and fire frequency. This in-turn forces changes on soil depth and its water holding capacity by altering the rate of fluvial erosion, which feeds back to soil moisture, vegetation cover, and fire frequency. LAI is the leaf area index, Ic is the infiltration capacity of the soil (as affected by fire and water repellence), and CO is soil cohesiveness (altered by fire).

4. Conclusion

We used the flammable landscapes of SE Australia to evaluate the role of fire in the coevolution of soil-forest systems. Using a new numerical model (CoolFlameS) that represents the eco-hydro-geomorphic processes that are typical to SE Australian forests, we (i) tested the hypothesis that fire-related processes are critical to explain the variations in coevolved systems states across an aridity gradient; (ii) identified the dominant fire-related processes and feedbacks involved in the coevolution process. CoolFlameS showed good skill in predicting patterns of soil moisture thresholds ecohydrological partitioning, fire frequency distribution, surface runoff, and erosion and denudation rates across a gradient of aridity when compared to local measurements and published data (see Inbar et al. 20 for details). The validated model was then used to conduct numerical experiments to address the aims. The results showed that (i) the hypothesis was supported and that the relative role of fire in coevolution of soil depth and forests increased with aridity in the study area; (ii) among the three effects of fire examined, the relative role of post-fire reduction in infiltration capacity (and its effects of surface runoff and fluvial erosion rates) on coevolution of soil-vegetation systems was the largest, followed by post-fire reduction in soil cohesiveness and canopy cover; and the trajectory and magnitude of the coevolution of soil-vegetation systems are driven by a climatically driven feedback between soil, vegetation, and fire. For example, under a drying climate, long-term increase in post-fire erosion might contribute to more frequent fires and more erosion. We conclude that incorporating fire-related processes and feedbacks is essential when using models to investigate the critical zone and landscape evolution in fire-prone landscapes.

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