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Responsess of *Digitaria sanguinalis* (L.) Scop growth and soil respiration dynamics to ash content in a burned area

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Abstract

Background Global warming has significantly increased the frequency and scale of wildfires. However, the effects of fire residues on soil CO₂ emissions and the germination of pioneer species in burned areas have been insufficiently studied. Understanding these impacts is crucial for post-fire ecosystem recovery. This study examined the effects of wildfire ash from Liangshan Yi Autonomous Prefecture, China, on the germination of *Digitaria sanguinalis* (L.) Scop and soil respiration (*Rs*).

Results Within the applied ash gradient (0.00, 0.58, 1.16, 1.73 kg m⁻²), final germination of *Digitaria sanguinalis* was not significantly affected by ash, whereas precipitation exerted the dominant control. In contrast, early seedling growth showed a significant ash × precipitation interaction: under normal to moderately wet conditions, intermediate ash loading (≈0.58 and 1.16 kg m⁻²) promoted plant height, but this effect disappeared under the driest or wettest scenarios. Across all precipitation regimes, *Rs* increased with ash loading and showed an early rise, a mid-term peak, and a later stabilization or decline as ash-derived substrates were depleted. *Rs* was strongly related to 5 cm soil temperature, whereas, no significant monotonic association between *Rs* and 5 cm soil moisture was detected within the moisture conditions maintained by the precipitation treatments, suggesting that temperature explained more of the short-term variability in *Rs*. The temperature sensitivity (*Q*₁₀) of *Rs* also increased with ash addition, with values of 1.30, 1.82, 2.18, and 2.34 for the four ash treatments.

Conclusions Wildfire ash within a realistic post-fire range did not significantly inhibit the germination of the pioneer grass *D. sanguinalis*, which was mainly controlled by precipitation, but moderate ash loading (0.58, 1.16 kg m⁻²) supported early seedling growth under adequate moisture. At the same time, ash inputs enhanced *Rs* and increased its apparent temperature sensitivity, with *Rs* being predominantly driven by soil temperature and with moisture effects not emerging as a detectable monotonic trend within the experimental moisture window. These findings suggest that, in water-limited dry-valley ecosystems, complete removal of surface ash to avoid potential germination inhibition is unnecessary; instead, management should prioritize maintaining soil moisture while allowing moderate ash to remain on the surface to support early post-fire recovery and to improve the representation of ash effects in soil respiration models for fire-affected forests.

Keywords Crabgrass (*Digitaria sanguinalis* (L.) Scop), Seed germination, Soil respiration, Wildfire ash

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Resumen

Antecedentes El calentamiento global ha incrementado significativamente la frecuencia y escala de los incendios de vegetación. Sin embargo, los efectos de los residuos en las emisiones de CO₂ y la germinación de especies en áreas quemadas han sido insuficientemente estudiados. El entender esos impactos es crucial para la recuperación de los ecosistemas en el post fuego. Este estudio examinó los efectos de las cenizas provenientes de un incendio en la prefectura autónoma de Liangshan Yi, en China, sobre la germinación de *Digitaria sanguinalis* (L.) Scop y sobre la respiración del suelo (Rs).

Resultados Dentro del gradiente de aplicación de esas cenizas (0.00, 0.58, 1.16, 1.73 kg m⁻²), la germinación final de *Digitaria sanguinalis* no fue afectada significativamente por esas cenizas, mientras que la precipitación fue la que ejerció el control dominante en la germinación. Como contraste, el crecimiento inicial de las plántulas mostró una interacción significativa entre cenizas y precipitación: bajo condiciones de humedad normales a moderadas, la carga intermedia de cenizas (≈0.58 and 1.16 kg m⁻²) promovió la altura de las plantas, aunque este efecto desapareció bajo escenarios muy secos o muy húmedos. A través de todos los regímenes de precipitación, Rs se incrementó con el aumento en la carga de cenizas y mostró un rápido incremento, un pico a mediados del experimento, luego una estabilización o declinación a medida que los sustratos de las cenizas se iban consumiendo. La Rs fue fuertemente relacionada con la temperatura en los primeros 5 cm del suelo, mientras que no hubo una asociación monotónica detectada entre Rs y la humedad en los primeros 5 cm del suelo mantenida por los tratamientos de precipitación, lo que sugiere que la temperatura explica más sobre la variabilidad de la Rs a corto plazo. La sensibilidad a la temperatura (Q₁₀) de la Rs también se incrementó con la adición de cenizas, con valores de 1,30; 1,82; 2,18; y 2,34 para los cuatro tratamientos de cenizas.

Conclusiones Los fuegos de vegetación, dentro del rango de un post fuego realista, no inhiben significativamente la germinación de la especie pionera *D. sanguinalis*, la que fue principalmente controlada por la precipitación, aunque una carga moderada de cenizas (entre 0,58 y 1,16 kg m⁻²) favorecieron el crecimiento temprano de las plántulas bajo una moderada humedad del suelo. Al mismo tiempo, la adición de cenizas aumentó la Rs e incrementó su temperatura sensible aparente con Rs siendo predominantemente direccionada por la temperatura del suelo, mientras que los efectos de la humedad no emergieron como una tendencia monotónica dentro de ventana experimental de humedad. Estos resultados sugieren que, en ecosistemas de valles secos, limitados por la falta de humedad, la remoción completa de la capa superficial de cenizas para eliminar la potencial inhibición de la germinación es innecesaria; en cambio, el manejo debería priorizar mantener la humedad de suelo permitiendo que una moderada cantidad de cenizas permanezcan en la superficie para favorecer la recuperación temprana en el post fuego y para mejora la representación de los efectos de las cenizas en la respiración del suelo en Bosques afectados por incendios.

Introduction

Climate warming has significantly increased the frequency and intensity of forest fires (Masson-Delmotte et al. 2021). Globally, approximately 1% of forests are affected by fire annually (Crutzen et al. 1979; Chen et al. 2020), which contributes significantly to global carbon emissions from biomass combustion and is one of the key drivers of variation in carbon fluxes in forest ecosystems (Van der Werf, Randerson et al. 2010). Forest soils store about 67% of the terrestrial organic carbon (Hu T, Zhao B et al. 2021), and play a critical role in the global carbon cycle and climate regulation.

Soil respiration (Rs)—the primary pathway by which forests release CO₂—includes heterotrophic respiration from the decomposition of litter, dead plant material, roots, and soil organic matter, as well as autotrophic respiration from root growth and biomass (Ngaba et al. 2023). Even minor changes in Rs can significantly affect atmospheric CO₂ levels, creating feedback effects on the

global carbon balance and the process of climate change (Bouskill et al. 2020). Forest fires alter both abiotic factors (e.g., temperature, moisture, substrate availability) and biotic factors (e.g., soil microbes, biomass), thereby impacting Rs and further influencing the overall carbon-cycling process in forests (Sun L, Hu T et al. 2014, Hu Z, Liu S et al. 2018).

Despite extensive research on how fire-induced changes affect Rs, the specific influence of fire-produced ash has received little attention. Ash, a major post-fire residue, can both supply nutrients that stimulate microbial activity and soil respiration (Rs) and provide pyrogenic carbon (Pyc) that may accelerate the decomposition of native soil organic matter (Mataix-Solera et al. 2009). Studies conducted in different ecosystems have reported varying effects of ash on soil respiration. For example, studies in African savannas have shown that adding wildfire ash can enhance Rs by enriching soil nutrients (Andersson et al. 2004; Sánchez-García et al.

2021), whereas research in a Mexican tropical deciduous forest observed a decrease in R_s —possibly due to inhibitory chemical components in the ash reducing microbial activity (García-Oliva et al. 1999).

Moreover, the above studies have focused solely on the input of wildfire ash, without considering that the specific contribution of ash to R_s cannot be isolated from the process of vegetation recovery (Sánchez-García et al. 2020). Ash has been shown to affect seed germination in many species (Naghipour et al. 2016). In particular, the by-product ethylene in ash after being moistened can promote the germination and growth of plants (Ne'Eman, Henig-Sever et al. 1999). However, studies such as Omid et al. (2022) reported that significant differences in species germination responses to ash were found in semi-arid oak forests in western Iran. Ne'Eman et al. (1999) found that a thick layer of ash significantly inhibited seed germination of *Cistus salviifolius*, *C. reticus*, and *P. halepensis*. This may be due to high osmotic pressure lowering the water potential, thereby preventing water from entering the seed embryo, or due to the toxic effects of harmful substances produced in the ash. Together, these contrasting results show that ash effects on seed germination are highly context dependent, while most existing work comes from laboratory Petri-dish experiments, leaving the real impact of wildfire ash on seedling emergence in burned soils poorly constrained.

During the early stages of ecological restoration, the emergence of pioneer species is vital for soil formation and establishes conditions favorable for subsequent species (Ogwayo 2023). Rapidly growing pioneer plants can stabilize soil structure, improve soil conditions, and promote soil development (Fernández-García et al. 2021). They also enhance soil microbial activity and enzyme activity, reducing the loss of key nutrients such as nitrogen and phosphorus (Min et al. 2023). These functions not only lay a stable foundation for later community succession but also have an important impact on the dynamic trajectory of R_s . Thus, investigating the role of ash in the germination of pioneer species is of great scientific importance for post-fire ecological restoration.

Liangshan Yi Autonomous Prefecture in Sichuan Province is a typical ecologically vulnerable region in southwestern China, where frequent forest fires significantly disturb local ecosystems each year (Kun et al. 2021). The special climatic conditions in this area, along with human-conducted controlled burns, make the problems of ash coverage after fires and soil nutrient loss particularly prominent. However, in Liangshan's dry-hot valley forests, the response of R_s to wildfire ash has not been quantified, and no study has jointly examined how ash and altered precipitation regimes affect both pioneer grass establishment and soil CO_2 efflux during early

post-fire recovery. Here, we use burned-site soil and wildfire ash from Liangshan to test how a realistic gradient of surface ash loading and manipulated precipitation jointly influence the germination and early growth of the pioneer grass *Digitaria sanguinalis* and the accompanying dynamics of soil respiration. Therefore, investigating how fire residues affect the germination of *D. sanguinalis* will provide strong scientific support for post-fire ecological restoration. Other studies have shown that *D. sanguinalis*, as a C4 plant, has special advantages in fixing CO_2 through C4 photosynthesis (King and Oliver 1994; Balogun et al. 2021). Some studies have pointed out that C4 plants make greater contributions to soil carbon sequestration compared with C3 plants (Al Souki et al. 2021). Therefore, the growth of *D. sanguinalis* in forest burn areas may have an important impact on R_s .

Due to the different degrees of damage to soil structure and properties caused by different fire intensities, as well as the precipitation changes induced by climate change, the water-retention capacity of soil has changed significantly during the post-fire recovery process, thus having different degrees of impact on the subsequent germination and growth of species. To address these questions, we conducted a pot experiment using burned-site soil and wildfire ash under a factorial combination of multiple ash loads and precipitation regimes that bracket the local range of early-summer rainfall in Liangshan. The scientific problems intended to be solved in this study: (1) Whether ash promotes or inhibits the germination of *D. sanguinalis* in burned-site surface soil under controlled conditions; (2) How R_s responds to varying levels of ash input; (3) The phase-specific dynamics of R_s under the combined influences of *D. sanguinalis* germination and ash degradation, as well as the regulatory roles of soil temperature and moisture.

Hypotheses

Based on previous studies of ash-seed interactions and post-fire soil CO_2 efflux, we propose the following testable hypotheses for this factorial experiment: (i) within a realistic range of surface ash loading in dry-valley forests, the germination of *D. sanguinalis* would be primarily controlled by water availability and relatively tolerant to ash cover, whereas early seedling growth would be more sensitive to ash $\times$ precipitation interactions, with moderate ash promoting seedling height under normal to moderately wet conditions; (ii) wildfire ash inputs would stimulate soil respiration and increase its apparent temperature sensitivity (Q_{10}) by supplying labile substrates and nutrients to microbial communities; and (iii) during the early post-fire recovery stage, R_s would show an exponential positive relationship with 5 cm soil temperature (T_s) and be more strongly regulated by temperature

than by 5 cm soil moisture (W_s) within the range of moisture conditions considered in this study.

Experimental design and methods

Study area

The study area is located in Liangshan Prefecture in southwestern China ($102^{\circ}11' \sim 102^{\circ}43' \text{ E}$, $27^{\circ}53' \sim 28^{\circ}32' \text{ N}$) (Fig. 1). This region has a subtropical monsoon climate, characterized by large daily temperature range and small annual temperature range, with an average annual temperature of 14°C . The multi-year mean annual precipitation is 1006 mm, whereas the mean annual potential evaporation is 1945 mm; more than 80% of the rainfall occurs between May and October, with an uneven seasonal distribution and high evaporative demand. Long-term mean monthly temperature and precipitation for the region are shown in Fig. 1. Precipitation data were obtained from the 1-km monthly precipitation dataset for China (Peng 2020), and air temperature data were derived from

the NOAA National Centers for Environmental Information (NCEI) Global Surface Summary of the Day (GSOD) dataset (National Centers for Environmental Information (NCEI) 2025). The landscape of Liangshan is predominantly composed of low- to medium-mountain terrain, which covers approximately 70% of the area. The main soil types are purple soil and yellow-brown soil. The burned site from which the experimental materials were collected is located in Luoli Village, Lizi Township, Xide County, Liangshan Prefecture ($102^{\circ}12'42'' \text{ E}$, $28^{\circ}02'09'' \text{ N}$). This collection site is characterized by low- to medium-mountain terrain at an elevation of approximately 2400 m and features acidic yellow-brown soil. The experimental soil used in the pots was collected from the 0–20 cm layer of the burned site described above, and gently processed to obtain a homogeneous substrate while retaining its main physicochemical characteristics. The burned areas are mainly composed of tropical arbors, shrubs and herbs. The dominant arbor species is *Eucalyptus*

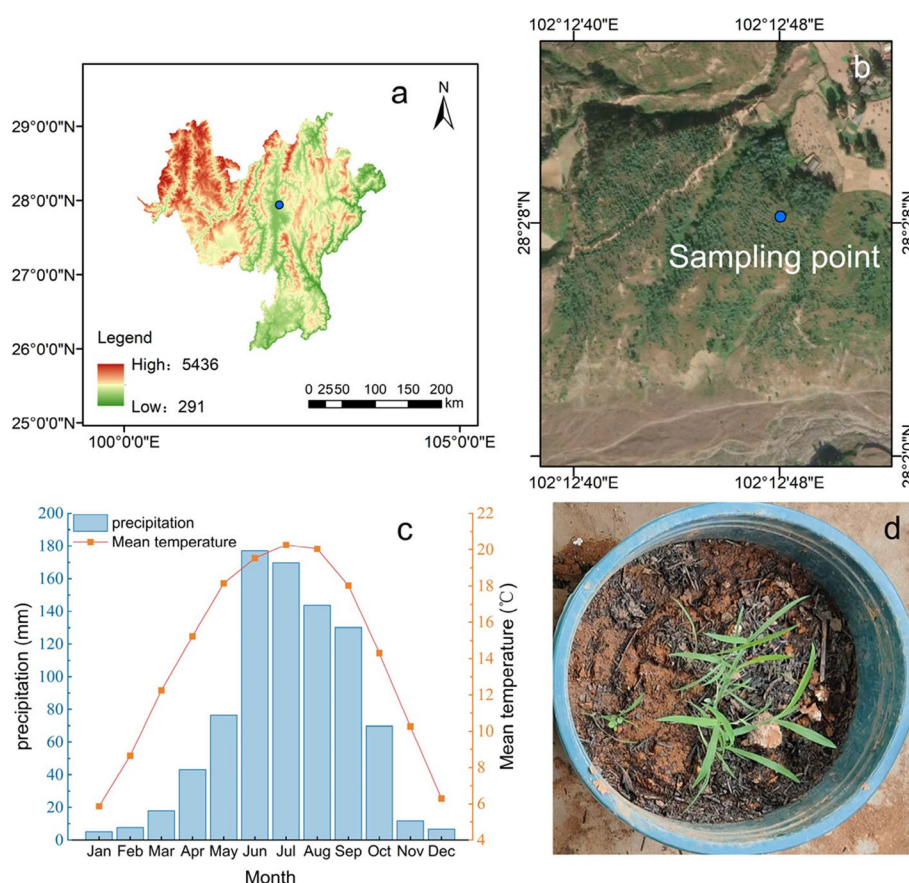


Fig. 1 **a** Location of the study area in Liangshan Prefecture, Southwest China, with elevation shown by a digital elevation model. **b** High-resolution satellite image of the burned site and experimental plot (blue dot). **c** Climatic diagram for Xide County showing mean monthly precipitation (bars) and mean air temperature (line) during 2005–2023. **d** Pot-grown individuals of the target species *Digitaria sanguinalis* under the ash $\times$ precipitation treatments, illustrating the surface ash top-dressing on burned soil

robusta Smith, the dominant shrub species is *Ageratina adenophora*, and the dominant herbaceous species are *Paspalum distichum* L. and *D. sanguinalis*.

Experimental setup and data measurement

Digitaria sanguinalis seeds used in this study were purchased in April 2024 from Danxin Agricultural Technology Co., Ltd. (Nangong, Hebei, China). Prior to the experiment, seeds were kept sealed in a dry, dark environment and stored short term at 4 °C. Immediately before sowing, seeds were surface-sterilized as follows: immersion in 70% (v/v) ethanol for 30 s with gentle agitation, followed by immersion in 1% sodium hypochlorite solution (available chlorine) for 5 min. The seeds were then rinsed 3–5 times with sterile distilled water and blotted dry on sterile filter paper. Understory litter and fine twigs/herb–shrub materials were collected from the soil surface of a burned site in Xide County, Liangshan Prefecture (Sichuan, China). Only clean surface fuels were taken, avoiding mineral soil and gravel. The material was transported to the laboratory and pre-dried at 45–50 °C for 24 h to constant mass. Combustion was conducted outdoors in a well-ventilated area: dried material was placed on a heat-resistant stainless-steel tray and ignited, allowed to self-burn until no visible flame remained and the residue turned grey-white, then allowed to cool naturally. Incompletely burned char fragments (>2 mm) were removed, and the residue was sieved through a 2-mm mesh to obtain fine ash. The ash was immediately sealed in airtight bags and homogenized before use (coning-and-quartering) to minimize heterogeneity arising from fuel differences. Surface dead branches, leaves, and vegetation were removed from the burned site, and soil samples were excavated from the 20-cm depth. The soil was thoroughly mixed and then passed through a 2-mm sieve to remove large impurities, plant roots, and stones. The sieved soil was then left to rest for 5 days to ensure that any remaining plant roots died and microbial activity stabilized. The processed soil was placed into plastic pots (internal diameter 23 cm, height 17 cm), with each pot containing approximately 4.2 kg of soil.

Ash was applied as a uniform surface top-dressing (not mixed into the soil). Ash loadings were defined by mass per unit area based on the pot surface area (346 cm²) at four levels: A1=0.00 kg m⁻² (0.0 Mg ha⁻¹), A2 ≈ 0.58 kg m⁻² (5.8 Mg ha⁻¹), A3 ≈ 1.16 kg m⁻² (11.6 Mg ha⁻¹), and A4 ≈ 1.73 kg m⁻² (17.3 Mg ha⁻¹). Given the soil mass per pot (~4.2 kg), these ash loadings correspond to ash:soil mass ratios of approximately 0, 0.5, 1.0 and 1.4%, respectively. This imposed gradient from zero to high surface ash loading was designed to provide a mechanistic baseline (A1) and to isolate the directional effects of increasing ash input on germination and *Rs*, rather than to

reproduce a single field-measured “natural ash” level. Precipitation regimes were set as 50%, 100%, 150%, and 200% of the long-term mean May precipitation (116 mm, 2005–2023) in the study area, a gradient fully covering the historical interannual variation range of local May precipitation (47 mm minimum to 242 mm maximum, 2005–2023) to reflect natural dry-to-wet scenarios during the critical early post-fire germination period in the field. To implement these regimes in pots, the target cumulative monthly precipitation was evenly distributed across 31 days of May and converted to a fixed daily irrigation volume scaled by the pot surface area (346 cm²); this daily watering approach avoided extreme soil moisture fluctuations, surface runoff and nutrient leaching caused by episodic field rainfall, while maintaining cumulative water inputs consistent with natural monthly precipitation totals. The four treatments were set as R1=0.5×(65 mL pot⁻¹d⁻¹, ~1.9 mm d⁻¹/58 mm month⁻¹), R2=1.0×(130 mL pot⁻¹ d⁻¹, ~3.8 mm d⁻¹/116 mm month⁻¹), R3=1.5×(195 mL pot⁻¹ d⁻¹, ~5.6 mm d⁻¹/175 mm month⁻¹), and R4=2.0×(260 mL pot⁻¹ d⁻¹, ~7.5 mm d⁻¹/233 mm month⁻¹), with R1A1, R2A1, R3A1, and R4A1 serving as the respective controls for each precipitation regime in the analysis of ash effects on *D. sanguinalis* germination and soil respiration (*Rs*). In the analysis of the relationship among ash, *D. sanguinalis* germination, and *Rs*, the treatments R1A1, R2A1, R3A1, and R4A1 served as controls for the precipitation regimes R1, R2, R3, and R4, respectively. Each of the 16 treatments was replicated three times, yielding a total of 48 experimental samples (Table 1) (Fig. 2). Each pot was sown with 100 seeds of *D. sanguinalis*, and water was applied uniformly according to the assigned precipitation treatment. To determine the viability of the seed lot, we conducted an independent water-culture germination test in Petri dishes. Three replicates of 100 seeds were placed on

Table 1 Experimental factors and treatment levels (ash loading A and precipitation R) and replication

Precipitation	R1 (0.5 ×)	R2 (1.0 ×)	R3 (1.5 ×)	R4 (2.0 ×)
Ash	65 mL	130 mL	195 mL	260 mL
A1(0.00 kg m ⁻²)	R1A1	R2A1	R3A1	R4A1
A2(0.58 kg m ⁻²)	R1A2	R1A2	R3A2	R4A2
A3(1.16 kg m ⁻²)	R1A3	R2A3	R3A3	R4A3
A4(1.73 kg m ⁻²)	R1A4	R2A4	R3A4	R4A4

The experiment followed a 4 × 4 factorial design (four ash loading levels × four precipitation regimes), with *n* = 3 replicates per A × R combination and a total sample size of *N* = 48. Ash loading was defined by mass per unit surface area: A1 = 0.00 kg m⁻² (0.0 Mg ha⁻¹), A2 ≈ 0.58 kg m⁻² (≈ 5.8 Mg ha⁻¹), A3 ≈ 1.16 kg m⁻² (≈ 11.6 Mg ha⁻¹), and A4 ≈ 1.73 kg m⁻² (≈ 17.3 Mg ha⁻¹). Precipitation amounts were set as multiples of the long-term mean May precipitation (monthly total, 2005–2023): R1 = 0.5 × (65 mL pot⁻¹), R2 = 1.0 × (130 mL pot⁻¹), R3 = 1.5 × (195 mL pot⁻¹), and R4 = 2.0 × (260 mL pot⁻¹)

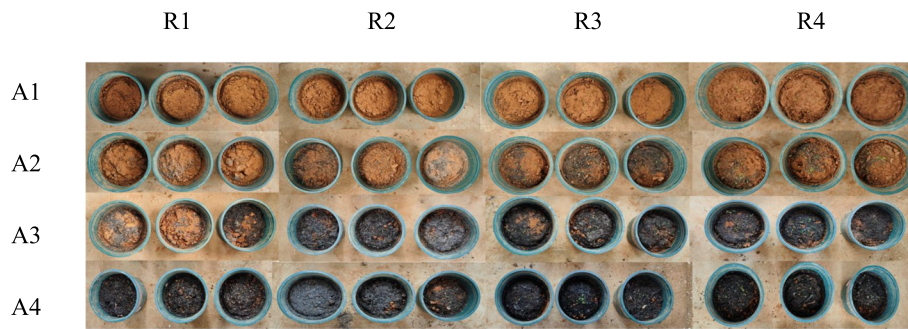


Fig. 2 Germination of *Digitaria sanguinalis* (L.) Scop seeds under Controlled Laboratory Conditions. Treatments A1, A2, A3, and A4 corresponded to ash additions of 0.00 kg m⁻², 0.58 kg m⁻², 1.16 kg m⁻², and 1.73 kg m⁻², respectively, while R1, R2, R3, and R4 represented precipitation levels of 65 ml, 130 ml, 195 ml, and 260 ml, respectively. (Photographed in May 2024, Liangshan Soil Erosion and Ecological Restoration in Dry Valleys Observation and Research Station, Xide, China. Photographer: Huanhuan Qi)

moistened filter paper in 12 cm Petri dishes, which were kept continuously saturated with distilled water and incubated under optimal laboratory conditions. Seeds with a visible radicle were counted as germinated. The average germination proportion in this test was 86%, which we treated as the viability of the seed batch. This viability value was used as the denominator when calculating germination percentages in the pot experiment. In this experiment, the plant height of *D. sanguinalis* was measured using a manual ruler. The ruler was placed vertically against the base of *D. sanguinalis* and the vertical distance from the top to the ground was recorded.

R_s was monitored using the GASMET GT5000 portable multiparameter soil respiration measurement system (GT5000, GASMET Technologies Oy, Helsinki, Finland), which comprises a GASMET GT5000 Fourier-transform infrared (FTIR) gas analyzer, a soil respiration chamber, and a tablet computer. The gas analyzer employed infrared spectroscopy to measure gas concentrations every 6 s, with each measurement lasting 3 min 25 s. The tablet computer, running the Calcmeter software, connects to the gas analyzer via Bluetooth and records all spectral data. During each measurement, a PVC ring (20 cm in diameter, 12 cm in height) was inserted into the pot, so that 2 cm was embedded and 10 cm remained above the surface. The soil respiration chamber was then securely placed over the PVC ring to form a sealed environment. Two Teflon tubes connected the sealed chamber to the gas analyzer to facilitate gas circulation. Each time during measurement, ultra-high-purity nitrogen was used to calibrate the gas analyzer. After each measurement, ultra-high-purity nitrogen was used again to clean the analyzer. Two replicates from each treatment group were randomly selected for measurement, resulting in 32 experimental samples being measured daily. Soil temperature and moisture were measured using a soil composition analyzer (TZS-PHWY-7G, Zhejiang Topu

Yunnong Technology Co., Ltd., Zhejiang, China) by inserting the probe vertically into the soil at a depth of 5 cm, with three measurements taken per pot. Measurements for R_s as well as soil temperature and moisture were conducted daily between 08:00 and 12:00. Monitoring continued for 42 days, until the germination phase of *D. sanguinalis* was complete and R_s had stabilized.

Data processing

For each treatment, the germination rate was calculated by dividing the number of germinated seeds by the number of viable seeds (86) and then multiplying by 100% (Cruz et al. 2022):

$$G = \text{number of germinated seeds} / \text{total number of seeds} * 100\% \quad (1)$$

The relationship between R_s under different ash treatments and the corresponding soil temperature was fitted using an exponential model (Van't Hoff 1884):

$$R_s = ae^{bT} \quad (2)$$

In the equation, R_s is the soil respiration rate, T is the 5 cm soil temperature (°C) corresponding to soil respiration, and a and b are fitted parameters.

The temperature sensitivity of soil respiration is defined as the factor by which R_s increases when the temperature rises by 10 °C. The temperature sensitivity coefficient (Q_{10}) was calculated as (Van't Hoff 1884):

$$Q_{10} = e^{10b} \quad (3)$$

The relationship between R_s and soil moisture was described using the following model (Davidson et al. 1998):

$$R_s = aW + b \quad (4)$$

In the equation, W is the soil moisture at 5 cm corresponding to R_s , and a and b are fitted parameters.

Variance analysis was performed using SPSS 27.0 (SPSS Inc., Chicago, IL, USA), and Duncan's multiple comparison test was used to evaluate statistical differences between group means. In addition, two-way ANOVA was conducted to test the main and interactive effects of ash level and precipitation regime on germination rate and other response variables, with a significance level set at $p < 0.05$. Exponential models, linear regression, and curve fitting were applied to analyze relationships between R_s and T_5 and W_5 , and Pearson correlation analysis was conducted to assess the relationship between R_s and different ash gradients.

Results

The effects of different ash gradients on the germination of *D. sanguinalis*

Under 1.5× and 2× rainfall conditions, *D. sanguinalis* seeds emerged from the soil as early as day 4 under different ash treatments. However, under 1× and 0.5× rainfall conditions, seedling emergence was delayed until days 5–7. On day 11 of the experiment, a small number of seeds germinated, with a particularly noticeable effect in the R1 and R2 groups. As shown in Table 2, the germination response of *D. sanguinalis* to the ash gradient exhibited some fluctuations among precipitation regimes, but no consistent monotonic pattern was observed overall. In the R1 and R2 treatments, germination rates increased slightly from A1 to A3 and then declined at the highest

ash level (A4), with overall differences remaining limited. In the R3 treatments, germination rates fluctuated slightly with increasing ash loading but generally remained close to the control level. In R4, germination rates in A2 and A3 (15.12% and 12.79%, respectively) were significantly higher than in A1 (10.47%) ($p < 0.05$), whereas A4 decreased again toward the control level. The two-way ANOVA showed that the main effect of ash loading on final germination percentage was not significant ($F = 0.18$, $p = 0.91$), nor was the ash × precipitation interaction ($F = 0.58$, $p = 0.80$), whereas precipitation had a significant effect ($F = 15.57$, $p < 0.001$; Table 4). These results indicated that, within the range of ash additions tested in this study, *D. sanguinalis* germination was primarily controlled by water availability and was relatively tolerant to surface ash cover.

As shown in Table 3, the plant height of ash-treated samples (A2: 2.39 cm, A3: 2.78 cm, A4: 2.30 cm) was higher than that of the control sample R1A1 (A1: 0.83 cm) ($p < 0.05$). The average plant height of R2A1 was the lowest among all treatments. There was no significant difference in plant height among the R2 treatment groups ($p > 0.05$). However, the plant height of ash-treated samples (A2: 2.28 cm, A3: 2.62 cm, A4: 2.86 cm) was higher than that of the control sample R2A1 (A1: 2.08 cm), and plant height increased with the amount of ash applied. In the R3 treatment group, R3A3 (3.11 cm) was significantly taller than R3A2 (1.93 cm) ($p < 0.05$), and other treatment

Table 2 Germination rate of *Digitaria sanguinalis* seeds under four treatment groups (R1, R2, R3, R4)

Precipitation Ash	R1 (0.5×) Germination rate (%)	R2 (1.0×) Germination rate (%)	R3 (1.5×) Germination rate (%)	R4 (2.0×) Germination rate (%)
A1	(1.55 ± 1.345) ^a	(8.92 ± 1.776) ^a	(12.40 ± 9.685) ^a	(10.47 ± 1.165) ^b
A2	(2.33 ± 0.23) ^a	(9.30 ± 7.627) ^a	(10.85 ± 2.924) ^a	(15.12 ± 2.325) ^a
A3	(2.72 ± 0.670) ^a	(11.24 ± 4.689) ^a	(8.531.777) ^a	(12.79 ± 1.160) ^a
A4	(2.33 ± 2.325) ^a	(9.30 ± 5.068) ^a	(12.02 ± 3.554) ^a	(10.08 ± 1.345) ^{ab}

A1–A4 denote ash loading levels as in Table 1; R1–R4 denote precipitation regimes as in Table 1. Each A × R combination had $n = 3$; values are means ± standard error (SE). Within a given precipitation regime (within-column), different lowercase letters indicate significant differences among ash loading according to Duncan's multiple range test ($p < 0.05$); the same letter indicates no significant difference. Germination percentages in pots were calculated relative to the number of viable seeds determined from Petri-dish water-culture tests (mean seed viability 86%). For each precipitation regime, A1 (no ash) served as the control

Table 3 Plant height of *Digitaria sanguinalis* under four treatment groups (R1, R2, R3, R4)

Precipitation Ash	R1 (0.5×) Plant height (cm)	R2 (1.0×) Plant height (cm)	R3 (1.5×) Plant height (cm)	R4 (2.0×) Plant height (cm)
A1	(0.83 ± 0.329) ^b	(2.08 ± 0.461) ^a	(2.42 ± 0.335) ^{ab}	(2.42 ± 0.656) ^b
A2	(2.39 ± 0.535) ^a	(2.28 ± 0.481) ^a	(1.93 ± 0.198) ^b	(2.72 ± 0.185) ^{ab}
A3	(2.78 ± 0.479) ^a	(2.62 ± 0.336) ^a	(3.11 ± 0.840) ^a	(3.22 ± 0.207) ^a
A4	(2.3 ± 0.361) ^a	(2.86 ± 0.476) ^a	(2.81 ± 0.576) ^{ab}	(2.37 ± 0.473) ^b

A1–A4 denote ash loading levels as in Table 1; R1–R4 denote precipitation regimes as in Table 1. Each A × R combination had $n = 3$; values are mean ± standard error (SE). Within a given precipitation regime (within-column), different lowercase letters indicate significant differences among ash loading by Duncan's multiple range test ($p < 0.05$). For each precipitation regime, A1 (no ash) served as the control

groups also had greater plant height than the control sample R3A1. In this treatment group, plant height first increased and then decreased as the ash application rate increased. In the R4 treatment group, R4A3 (3.22 cm) was taller than both R4A4 (2.37 cm) and the control sample R4A1 (2.42 cm) ($p < 0.05$). Two-way ANOVA confirmed significant main effects of both ash loading ($F = 9.81$, $p < 0.001$) and precipitation regime ($F = 3.93$, $p = 0.017$) on final seedling height, as well as a significant ash $\times$ precipitation interaction ($F = 2.65$, $p = 0.020$; Table 4). These results indicate that early growth of *D. sanguinalis* was jointly regulated by ash and water availability, and that the positive effects of moderate ash loading on seedling height were dependent on the precipitation regime.

Diurnal variation characteristics of R_s rate under different ash treatments

Starting from the second day, as *D. sanguinalis* seeds germinated on a large scale, R_s in all treatment groups reached the first peak. During this stage (days 2–9), R_s was at its highest level throughout the entire experiment. Between days 10 and 19, R_s showed a second peak. In the R1 and R2 treatment groups, R_s exhibited a clear upward trend, which might have been related to the increase in temperature triggering a second wave of *D. sanguinalis* germination. In contrast, the number of newly germinated seeds was relatively lower in the R3 and R4 treatment groups. From day 20 to day 42, R_s in all treatments stabilized, decreasing to a certain level and remaining at that level for a long time (Fig. 3). During this stage, *D. sanguinalis* seed germination ceased, and the plants entered a stable growth phase. R_s showed an upward trend to varying degrees as the amount of ash applied increased. The increase was the largest in R(1–4) A4, followed by R(1–4)A3, R(1–4)A2, and the smallest in R(1–4)A1. During days 18 to 19, except for the control groups without ash application (R1A1, R2A1, R3A1,

R4A1), where R_s did not decrease, R_s in all other ash-treated groups decreased and approached the level of the control groups.

Response characteristics of R_s to different ash gradients

Pearson correlation analysis was conducted between R_s and ash content for the four treatment groups (R1, R2, R3, and R4). The correlation coefficients were 0.645, 0.686, 0.617, and 0.598, respectively. The average R_s values for the R1A(1–4) treatment group, the values were $0.320 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.466 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.583 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and $0.705 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For the R2A(1–4) treatment group were $0.329 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.470 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.630 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and $0.715 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For the R3A(1–4) treatment group, the values were $0.348 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.532 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.675 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and $0.784 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. For the R4A(1–4) treatment group, the values were $0.353 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.559 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $0.701 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and $0.840 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. As the amount of ash applied increased, the rise in R_s was highly significant ($p < 0.01$, Fig. 4a), indicating that ash application affected the soil carbon release process.

By comparing R_s on day 0 (immediately after ash and precipitation treatments were applied, before seedling establishment) and on day 42 (at the end of the 42-day pot experiment, after *D. sanguinalis* had grown) (Fig. 4b), the results showed that on the last day, R_s in R(1–4) A1 (0.297, 0.301, 0.325, 0.344) was lower than on day 0 (0.317, 0.366, 0.4, 0.384). However, on day 42, R_s in R1A(2–4) (0.44, 0.464, 0.555), R2A(2–4) (0.423, 0.539, 0.5), R3A(2–4) (0.446, 0.547, 0.555), and R4A(2–4) (0.482, 0.525, 0.568) was higher than on day 0: R1A(2–4) (0.423, 0.447, 0.507), R2A(2–4) (0.377, 0.5, 0.442), R3A(2–4) (0.422, 0.471, 0.269), and R4A(2–4) (0.435, 0.486, 0.399). Moreover, as the ash application rate increased, the difference between the two became larger.

The relationship between T_5 and W_5 factors and R_s

Across the 42-day monitoring period, the measured 5 cm soil moisture (W_5) varied consistently with both ash loading and precipitation treatments, with an overall range of 5.61%–41.46% across all experimental units. Specifically, the W_5 range was 5.90%–34.84% for A1 (0.00 kg m^{-2}), 5.91%–39.57% for A2 (0.58 kg m^{-2}), 6.52%–41.46% for A3 (1.16 kg m^{-2}), and 5.61%–39.83% for A4 (1.73 kg m^{-2}). Within each ash loading treatment, W_5 increased significantly with the rising precipitation gradient (R1 to R4), which was consistent with our experimental irrigation design. To better analyze the relationship between R_s and T_5 and W_5 factors, we combined data across all precipitation gradients under the same ash loading into four treatment groups: A1R(1–4), A2R(1–4), A3R(1–4),

Table 4 Two-way ANOVA of the effects of ash loading and precipitation on final germination percentage and seedling height of *Digitaria sanguinalis*

	Germination: F	Germination: P	Height: F	Height: P
Ash loading (A)	0.18	0.91	9.81	<0.001***
Precipitation (R)	15.57	<0.001***	3.93	0.017*
A $\times$ R	0.58	0.80	2.65	0.020*

A and R represent ash loading and precipitation regime, respectively; A $\times$ R is their interaction term. F and p are omnibus test statistics; the significance threshold is $\alpha = 0.05$. * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$ indicate significant, highly significant, and extremely significant differences, respectively

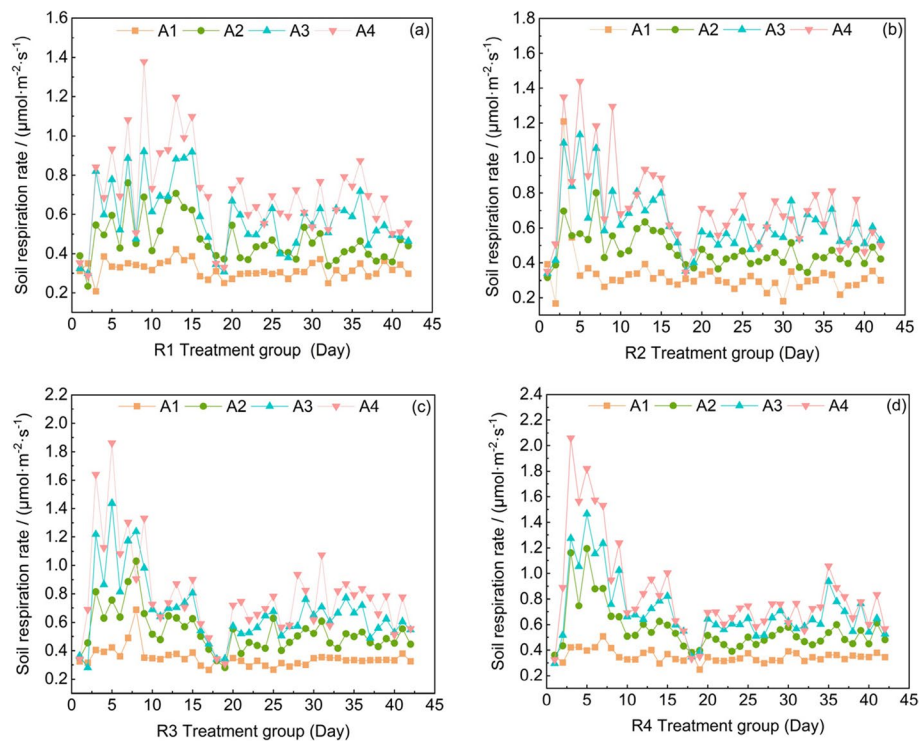


Fig. 3 Daily variation of soil respiration rate (R_s) during the germination period (42 days) in the four treatment groups (R1, R2, R3, R4). A denotes ash-loading level and R denotes precipitation regime; the numeric suffix indicates increasing treatment intensity (A1–A4: increasing ash loading; R1–R4: increasing precipitation level)

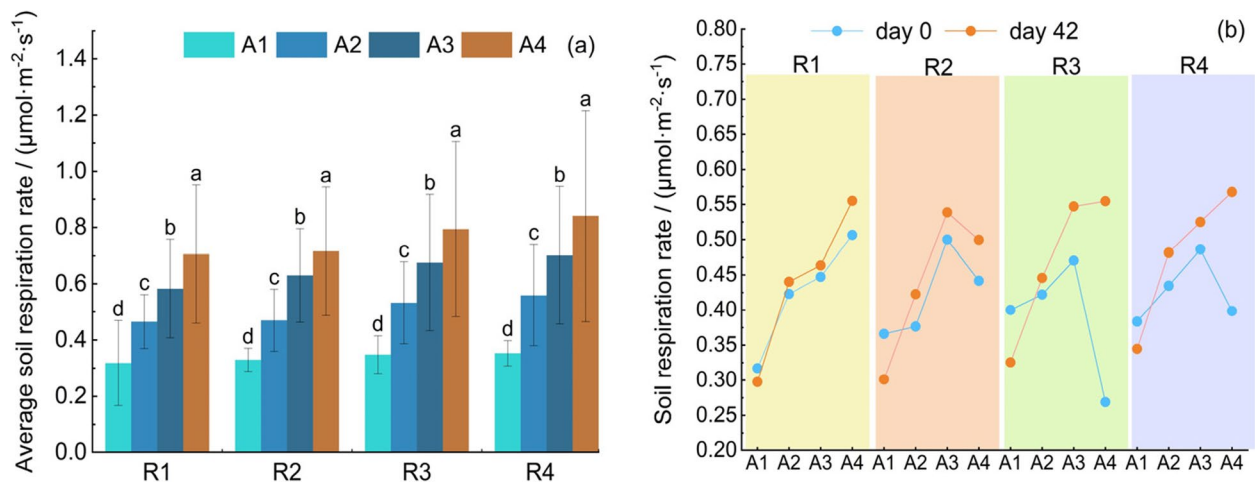


Fig. 4 **a** Comparison of the average soil respiration rate (R_s) across different ash gradients in the four treatment groups (R1, R2, R3, R4). Lowercase letters indicate significant differences ($p < 0.01$). **b** Comparison of soil respiration rate (R_s) between day 0 (immediately after ash and precipitation treatments were applied, before seedling establishment) and on day 42 (at the end of the 42-day pot experiment, after *D. sanguinalis* had grown). A denotes ash-loading level and R denotes precipitation regime; the numeric suffix indicates increasing treatment intensity (A1–A4: increasing ash loading; R1–R4: increasing precipitation input)

and A4R(1–4). Through the analysis of the exponential model of R_s and T_5 , it was found that there was a significant exponential positive correlation between R_s under all four treatments and T_5 ($p < 0.01$). The model analysis

results showed that T_5 respectively explained 52.7%, 52.5%, 75.2%, and 55.9% of the variation in R_s in treatment groups A1, A2, A3, and A4 (Fig. 5), indicating that T_5 was an important factor affecting R_s under different

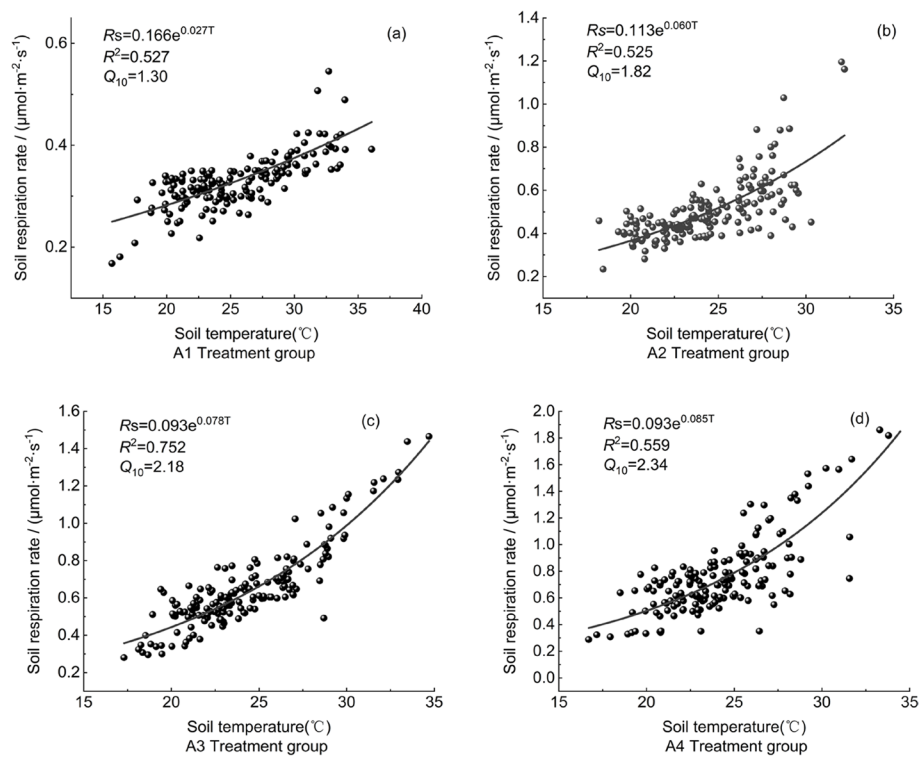


Fig. 5 Relationship between soil temperature and soil respiration rate (R_s). Q_{10} represents the temperature coefficient calculated using the van't Hoff exponential model. R^2 is the coefficient of determination for the exponential model of soil respiration rate in response to soil temperature

ash gradients. Further analysis of the temperature sensitivity index (Q_{10}) showed that the Q_{10} values of each treatment group were, in ascending order, A1R(1–4) $1.30 < \text{A2R}(1-4)$ $1.82 < \text{A3R}(1-4)$ $2.18 < \text{A4R}(1-4)$ 2.34 . This indicated that ash application at 0.58 kg m^{-2} , 1.16 kg m^{-2} , and 1.73 kg m^{-2} increased the Q_{10} of R_s to varying degrees.

The results of the linear regression analysis of R_s and W_5 show that although there was a linear positive correlation trend between R_s and W_5 under all four treatments, the correlations did not reach a significant level ($p > 0.05$), as shown in Table 5. This result indicates that under different ash gradient treatments, W_5 had a relatively weak ability to explain R_s .

R_s denotes soil respiration flux ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$); W is 5 cm soil water content (W_5 , %); T is 5 cm soil temperature (T_5 , °C); Q_{10} is the factor by which R_s increases for a 10°C rise in temperature; a and b are fitted regression coefficients; R^2 is the coefficient of determination.

Discussion

The influence of ash disposal on the germination and growth of *D. sanguinalis*

After a forest fire, the ground surface is covered by ash layers of varying thickness, which can play a crucial role in seed germination. Ash is generally the least studied factor among wildfire products. Most previous studies have reported two main outcomes regarding the effect of ash on germination: either no effect or clear inhibition

Table 5 Model parameters of the relationship between soil respiration rate ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), soil temperature (°C), and soil moisture (%) under different treatments

Treatment	$R_s = aW + b$			$R_s = ae^{bT}$			Q_{10}
	a	b	R^2	a	b	R^2	
A1	0.001	−0.019	0.005	0.166	0.027	0.527	1.30
A2	0.003	0.01	0.031	0.113	0.060	0.525	1.82
A3	0.002	0.257	0.008	0.093	0.078	0.752	2.18
A4	0.003	0.358	0.006	0.093	0.085	0.559	2.34

(González-Rabanal and Casal 1995, Reyes and Casal 1998, Reyes, Basanta et al. 2000, Reyes and Casal 2004). For example, Bargmann et al. () found that ash has a significant inhibitory effect on the germination of herbaceous plants. Riveiro et al. (2021) found that a small amount of ash does not affect seed germination, a moderate concentration of ash reduces germination, and a high concentration of ash completely inhibits seed germination. As a typical pioneer grass species in post-fire communities of the Liangshan dry-hot valley, *D. sanguinalis* was expected to experience the combined effects of residual ash cover and altered precipitation during early recovery. Our results showed that, within the applied range of ash additions, the final germination percentage of *D. sanguinalis* was not significantly affected by ash loading, whereas precipitation regime had a significant effect. Although germination under moderate ash levels was slightly higher than under the no-ash control in some precipitation treatments, the two-way ANOVA indicated that neither the main effect of ash nor the ash $\times$ precipitation interaction was significant. This suggested that, under our experimental conditions, *D. sanguinalis* seeds were relatively tolerant to surface ash cover and that germination was primarily constrained by water availability rather than directly controlled by ash input. This pattern was consistent with reports for some disturbance-tolerant or pioneer species that maintain germination capacity in post-fire environments; as long as soil moisture conditions were sufficient for imbibition and radicle emergence, moderate ash did not constitute a major limiting factor (Baskin and Baskin 2000; Bargmann et al. 2014; Piñas-Bonilla et al. 2024).

In contrast to the germination stage, seedling height exhibited a pronounced context-dependent response to the interaction between ash and precipitation. Moderate ash loading (e.g., A3) generally enhanced seedling height under normal or moderately elevated precipitation, whereas under the driest or wettest conditions this positive effect was weakened or disappeared. As a C_4 grass adapted to dry-hot valley environments, *D. sanguinalis* may not benefit from excessive moisture; under overly wet conditions, reduced soil aeration and constrained root functioning can limit nutrient uptake and growth, thereby offsetting the potential benefits of moderate ash additions in the wettest regime. The significant ash $\times$ precipitation interaction for seedling height indicated that early growth of *D. sanguinalis* could not be attributed to a single factor but resulted from the combined influence of ash inputs and water availability. On the one hand, ash may have promoted seedling growth by supplying available nutrients and modifying surface physicochemical conditions (Certini 2005; Bodí et al. 2014); on the other hand, drought stress or excessive moisture likely

constrained root activity and nutrient uptake, thereby offsetting the potential benefits of ash (Neary, Ryan et al. 2005). Taken together, the germination and seedling height results indicated that *D. sanguinalis* was able to establish across a relatively wide range of ash cover, whereas its subsequent growth was more sensitive to the specific combination of ash loading and precipitation regime, reflecting its adaptation as a post-fire pioneer and its responsiveness to moisture patterns.

It should be emphasized that this study was based on a controlled pot experiment, and we did not quantify detailed soil physical and chemical properties (e.g., bulk density, pH, water repellency) or fire-induced structural changes such as hydrophobic layers or compaction. Therefore, our findings are more appropriately interpreted as a mechanistic exploration of soil respiration and germination responses in homogenized burned soil under controlled pot conditions, rather than as a precise reconstruction of intact post-fire soil profiles. Nonetheless, our results indicate that *D. sanguinalis* exhibits high germination tolerance to realistic surface ash loading, whereas its early growth is more sensitive to ash-precipitation interactions. This suggests that, in water-limited dry-hot valley ecosystems, post-fire management does not need to remove surface ash excessively out of concern about inhibiting the establishment of this species and should instead focus on precipitation regimes and soil moisture conditions that support vegetation recovery.

Effects of ash on R_s rate and analysis of its diurnal variation characteristics

In all precipitation regimes, R_s increased significantly with the ash gradient, following the order: $R(1-4)A4 > R(1-4)A3 > R(1-4)A2 > R(1-4)A1$ ($p < 0.01$). This short-term stimulation of R_s by wildfire ash was consistent with studies reporting enhanced CO_2 efflux after ash addition in fire-affected ecosystems, where ash inputs increased the availability of nutrients and labile carbon substrates for soil microorganisms (Badía and Martí 2003; Sánchez-García et al. 2021). In our experiment, each pot contained the same soil mass (4.2 kg) and was sown with 100 *D. sanguinalis* seeds, and the soil was packed in a similar way in identical pots, so both bulk soil conditions and initial planting density were comparable across treatments. Thus, the divergence in R_s among ash $\times$ precipitation combinations mainly reflects how ash inputs and water availability modified microbial decomposition, root respiration and soil microclimate, rather than differences in soil or plant density. Similar patterns have been reported in post-fire field studies, where R_s varies strongly with ash inputs, surface warming and soil moisture even when stand density is comparable (Hu H, Hu T et al. 2016).

Ash likely affected soil respiration (R_s) through several concurrent mechanisms. First, the ash contained soluble organic compounds and mineral nutrients and raised surface-soil pH, which created a more favorable chemical environment for microbial metabolism (Certini 2005; Mataix-Solera et al. 2009; Bodí et al. 2014). Second, the ash carried a fraction of pyrogenic organic matter (PyOM) that can induce a positive priming effect after entering the soil, accelerating the mineralization of native soil organic matter and directly increasing heterotrophic respiration (R_h) (Maestrini et al. 2015). Under ash addition, the relative contribution of R_h to total R_s may therefore have increased, which is consistent with the short-term rise of R_s that we observed at higher ash loading. In addition, ash application coincided with the germination and early growth of *D. sanguinalis*; at moderate ash loading seedlings performed better, and root respiration plus rhizodeposition supplied fresh, labile carbon to the soil (Ren, Ding et al. 2020).

Over the 42-day monitoring period, R_s showed a clear stage-wise pattern. The initial peak shortly after sowing likely reflected the rapid use of labile substrates and the respiratory surge associated with seed imbibition and germination. A second peak around days 10–19 coincided with rising temperatures and continued emergence and seedling growth of *D. sanguinalis*, especially under intermediate moisture, indicating an overlay of warming and enhanced biological activity. Later, as germination ended and ash-derived labile substrates were exhausted, R_s declined or stabilized across treatments, indicating that the ash stimulation of CO_2 efflux was mainly an early, transient effect under our conditions.

In the broader literature, the direction of post-fire R_s responses is context dependent. Under low to moderate fire severity or prescribed burning, a pulse of available substrates from ash and unconsumed litter, together with higher soil pH and stimulated microbial activity, often produces a short-term increase in R_s (Dalias et al. 2024). Under high-severity fire or severe drought, root mortality, structural damage, and hydrophobic layers can restrict aeration and microbial activity, so R_s often declines (Neary, Ryan et al. 2005; Zhou et al. 2023). In this study, we compared ash loading under similar packing and identical pot geometry, which minimized direct diffusion differences due to bulk density or structure. Under this near-equal-density premise, the remaining between-treatment differences more likely reflected chemical-biological processes (substrate quantity, quality, pH adjustment, microbial activity, and rhizosphere inputs). Overall, our results align with a short-term, low-to-moderate-severity, substrate-driven scenario; by contrast, with stronger fire or prolonged drought, damage to

roots and structure and limited aeration would make a decline in R_s more likely.

Although we did not quantify residual ash loading at specific burn sites, we defined treatments by unit-area mass loading rather than thickness to facilitate comparison with field conditions and modeling. Using the pot surface area of 346 cm^2 , our three ash levels (0.58, 1.16, and 1.73 kg m^{-2}) correspond to approximately 5.8, 11.6, and 17.3 Mg ha^{-1} . Field data show that prescribed burns typically produce ash loading of about $2\text{--}5 \text{ Mg ha}^{-1}$ (Quigley et al. 2019), whereas wildfires can reach 6, 16, and 34 Mg ha^{-1} as severity increases (Santín et al. 2015). Thus, our three ash levels represented low, medium, and relatively high realistic ranges for dry-valley systems, with the highest level serving as an upper-bound test. Because wind erosion, overland flow, and fuel/temperature variability create strong spatial heterogeneity in ash density, particle size, and compaction, expressing treatments as mass per area is more comparable and repeatable than using thickness alone (Bodí et al. 2014).

Finally, this pot study had clear limitations. We did not partition autotrophic and heterotrophic components of R_s , and we did not directly measure microbial biomass (e.g., MBC), key enzyme activities (e.g., dehydrogenase, β -glucosidase), or changes in organic carbon fractions. Therefore, the proposed pathway—ash inputs stimulating microbial activity, which increases heterotrophic respiration and, in turn, elevates total R_s and its temperature sensitivity (Q_{10})—should be viewed as a directional inference supported by the observed patterns and prior literature rather than a quantitative attribution. Future field or longer-term work that combines R_a/R_h partitioning with MBC and enzyme measurements will be valuable to test this mechanism.

The impact of T_s and W_s factors on R_s

Soil temperature and moisture are two critical abiotic factors influencing R_s . In this study, R_s in all treatments showed a significant positive exponential relationship with 5 cm soil temperature (T_s), indicating that, under the experimental conditions, soil temperature was the primary driver of short-term variations in R_s . The pronounced decline in R_s on days 18–19, which coincided with a temporary decrease in air and soil temperature, further supported the dominant role of temperature in controlling respiration. This result is consistent with previous studies reporting enhanced soil CO_2 efflux with increasing temperature during the growing season (Wang Z, Zhou M et al. 2021, Cui H, Hu W et al. 2024). It also aligns with the conceptual framework that temperature and moisture can act as independent or confounded controls of soil respiration, and that temperature may explain much of the short-term R_s

variability when other constraints remain moderate or relatively stable (Davidson et al. 1998).

5 cm soil water content (W_5) did not play a dominant regulatory role in this experiment. Although different precipitation levels were applied, the watering regimes were designed to maintain conditions that allow germination and early seedling growth, and the observations therefore likely captured a predominantly intermediate moisture domain rather than prolonged extremes (severe drought or near-saturation). Under such intermediate conditions, soil CO_2 efflux often exhibits weak or non-monotonic moisture sensitivity (e.g., plateau- or hump-shaped responses), and a simple monotonic (linear) relationship may not be statistically detectable (Skopp, Jawson et al. 1990, Moyano et al. 2013). Consequently, we did not observe a typical Birch effect (a short-term CO_2 pulse following the rewetting of previously dried soil) (Birch 1958), nor did we detect a significant monotonic association between R_s and W_5 ($p > 0.05$). Notably, under the highest precipitation treatment, elevated moisture may have slightly suppressed R_s by limiting gas diffusion and oxygen supply in soil pores, thereby partially offsetting any stimulation expected from greater water availability (Linn and Doran 1984, Skopp, Jawson et al. 1990). Overall, within the moisture window and timescale considered here, R_s was mainly driven by temperature, while moisture effects were secondary and context dependent.

In this study, within the tested ash gradient, the temperature sensitivity (Q_{10}) of soil respiration (R_s) increased with ash addition, indicating a stronger temperature response when ash-derived substrates were more available. This pattern aligns with the framework proposed by Eric A. Davidson and Ivan A. Janssens, who suggested that Q_{10} is largely controlled by substrate availability and the metabolic state of microbial communities (Davidson and Janssens 2006).

Mechanistically, ash addition likely increased the supply of labile carbon and nutrients and raised soil pH, thereby stimulating microbial activity and reducing substrate limitation. Under reduced substrate constraints, soil respiration tends to show stronger temperature dependence, resulting in higher apparent Q_{10} values (Maestrini et al. 2015, Ren, Ding et al. 2020).

Conclusion

This study integrated the germination ecology of a pioneer grass with soil respiration (R_s) dynamics to evaluate the influence of post-fire ash during early recovery in a dry-valley system. Within the applied ash range, the final germination of *Digitaria sanguinalis* was not significantly affected by ash alone, whereas precipitation exerted a clear dominant control. In contrast,

early seedling growth exhibited a significant ash $\times$ precipitation interaction: under normal to moderately wet conditions, intermediate ash loading promoted plant height, whereas under the driest or wettest scenarios this promotion was not evident.

Across all precipitation regimes, R_s increased monotonically with ash loading and followed a three-phase temporal pattern: an initial rise associated with seed imbibition/emergence; a mid-term peak accompanying continued warming and seedling growth; and a late stabilization or decline as labile ash-derived substrates were depleted. R_s was strongly related to 5 cm soil temperature, whereas soil moisture played a secondary role within the experimental range. The temperature sensitivity (Q_{10}) of R_s also increased with ash addition. Taken together, these patterns are broadly consistent with the working hypotheses proposed in the Introduction, while also indicating that the magnitude of ash effects on *D. sanguinalis* performance and R_s depends on precipitation regime and the early post-fire recovery stage considered here.

Ash treatments were defined by mass per unit surface area, and the selected loads fell within low-to-relatively high realistic post-fire ranges. These results suggest that, in water-limited dry-valley ecosystems, complete removal of surface ash to avoid potential inhibition of germination was unnecessary; under adequate moisture, moderate ash even supported early growth. From a management perspective, priority should be given to ensuring soil moisture availability.

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Authors' contributions

L.J., Q.F.C., and Z.B. reviewed and revised the manuscript, W.H.H. assisted throughout the experiment and data analysis, X.D.H., C.X.G., and O.Y.H.Y. provided financial support, and L.H., Y.A.Q., and D.Q.C. provided resources. Q.H.H. wrote the first draft.

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Data availability

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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