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Cite this: *Environ. Sci.: Processes Impacts*, 2022, **24**, 1110

A review of simulation experiment techniques used to analyze wildfire effects on water quality and supply†

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Received 2nd February 2022
Accepted 20th June 2022

DOI: 10.1039/d2em00045h

rsc.li/espi

This review addresses the critical knowledge gap of techniques simulating combustion and heating characteristics present in natural wildfires and their use in assessing postfire impacts on water quality and quantity. Our assessment includes both laboratory and plot-scale techniques with burn and rainfall simulation components. Studies included focus on advancing understanding of changes in chemical and physical properties of soil, as well as subsequent runoff changes. Advantages of simulation experiments include: overcoming logistical challenges of collecting *in situ* wildfire data, reducing the high spatial variability observed in natural settings (*i.e.*, the heterogeneity of burn intensity and the underlying vegetation and soil properties), and controlling the magnitude of key drivers of wildfire impacts. In sum, simulation experiments allow for more direct attribution of water quality and quantity responses to specific drivers than experiments conducted *in situ*. Drawbacks of simulation techniques include the limitation of observing only local-scale processes, the potential misrepresentation of natural settings (*i.e.*, lack of spatial variability in vegetation, soil structure, burn intensity, *etc.*), uncertainty introduced through experimental error, and subsequent challenges in upscaling results to larger scales relevant for water management. This review focuses primarily on simulation techniques, with the goal of providing a foundation of knowledge for the design of future simulation experiments.

Environmental significance

Wildfires affect water quality through increased concentrations of sediment, metals, nutrients, and dissolved organic matter in runoff. This can create hazards for drinking water treatment plants, reservoirs, and freshwater ecosystems. Laboratory- and plot-scale wildfire simulation experiments are a valuable tool used to study these effects. This review summarizes the state of the art of wildfire and rainfall simulation experiment methodologies, including the strengths and weaknesses of each technique. This knowledge can help inform researchers in the design of their own simulation experiments, ultimately informing water management efforts to prepare for and mitigate potential water-related impacts of future wildfires.

1 Introduction

Forested watersheds are an important source of high quality water for billions of consumers worldwide, providing nearly two-thirds of potable water in the U.S.[1,2] Forests serve to capture and store precipitation, lowering the risk of flooding events.[1] The natural filtration processes that occur in watersheds provide major economic benefits, saving an estimated 4.1 trillion USD per year globally in water treatment costs.[2,3]

Wildfires are a natural disturbance mechanism which support the long-term health of forested ecosystems,[4] but also can degrade stream water quality and alter runoff generation mechanisms. Wildfire-driven increases in sediment, dissolved organic matter (DOM), nutrients, and heavy metals[1,2,5–7] can necessitate investments in infrastructure and altered methods of treatment in water treatment plants,[2,8–11] diminish reservoir storage due to sediment filling, and disturb freshwater ecosystems.[1,12] Additionally, increased post-fire runoff generation can produce high peak flows, increasing flood risks.[14] These effects (Fig. 1) occur immediately after a wildfire, but impacts can persist for up to 10 years.[13]

In recent decades, an increase in wildfire size, frequency, and severity has been observed in certain forested regions—a trend predicted to continue.[15–18] For example, the mean

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† Electronic supplementary information (ESI) available. See https://doi.org/10.1039/d2em00045h

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annual burn area in the Western U.S. has doubled since 1984 and is projected to have a 24–169% increase in mean burn area by midcentury.[18–21] Current understanding of wildfire effects on water quality and supply is incomplete, such that research is critically needed to assist water managers in adaptation and mitigation strategies.[1,7,10]

Hindrances in the collection of post-wildfire *in situ* data—unstable terrain and road closures immediately after wildfires, lack of comparable pre-burn control data, and high natural spatial and temporal variability—have contributed to a lack of knowledge of wildfire effects.[2,10,11] Additionally, post-wildfire response varies greatly regionally due to differences in soil and vegetation regimes, as well as climate.[22] Thus, insights from an *in situ* study are generally not directly transferable to another geographic area. Limited information exists about post-wildfire water quality response, in particular, with most studies primarily focusing on DOM, nutrients, and metals—leaving the responses of microbial constituents and anthropogenic contaminants largely unknown.[23]

Laboratory- and plot-scale simulation experiments which replicate burning and combustion mechanisms present in natural wildfires, as well as raindrop kinetic energies and leaching effects similar to post-wildfire precipitation, offer an alternative analytical technique for estimating wildfire effects on water quality and supply.[2,7,24–28] Hereafter, these two types of simulation experiments will be referred to as wildfire and rainfall simulators, respectively. These studies primarily advance understanding of burn effects on small-scale soil and water physical and chemical properties. The controlled setting of these simulation experiments can overcome logistical issues associated with *in situ* studies, as well as provide insight into regionally-specific drivers by allowing for more precise

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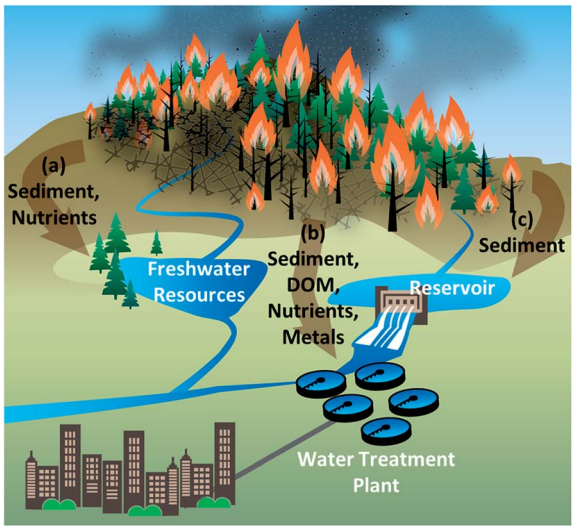

Fig. 1 Conceptual illustration of the impacts of wildfire on water quality and supply. The constituent fluxes in streams are driven by burning effects, affecting human and natural systems. Increased sediment and nutrient concentrations (a) drive eutrophication and disturb freshwater resources; increased sediment, DOM, nutrient, and heavy metal concentrations (b) can exceed water treatment plant treatment capacities; and increased sediment loads (c) affect reservoir storage capacity.

attribution of responses to controls. However, this type of analysis also presents new limitations, including dissimilarities to natural settings and difficulties in upscaling results to the catchment scale.[24,29]

2 Scope of review

The overarching scope of this review is to provide a critical assessment of existing laboratory- and plot-scale wildfire and rainfall simulation techniques used to measure the effects of wildfires on water quality and supply. Terminology is defined in Section 3, followed by a review of post-wildfire hydrologic and water quality responses in Section 4, including their implications for human and natural systems. Section 5 presents a review of simulation experiment techniques for both wildfire and rainfall processes, providing strengths and weaknesses for both laboratory- and plot-scale methods. Based on the merits of each method, recommendations for experimental design are provided in Section 6, followed by overall conclusions in Section 7.

A novel contribution of this review is the focus on methodological techniques—specifically, simulation experiments—used to generate and collect wildfire response data, rather than the data themselves.[13,30,31] We include brief analyses of common hydrologic and water quality response data from reviewed simulation experiment studies (a summary of the reviewed data is provided in the ESI†). However, this is not the focus of this review due to studies' wide ranges of research goals, temporal and physical scales, and key experimental factors—making useful cross-study comparisons difficult. Overall, this review is distinct from existing reviews, which primarily summarize the state of the art of wildfire effects on hydrology,[31–37] sediment transport and erosion,[12,13,38–40] and streamflow concentrations of DOM and nutrients (*i.e.*, nitrogen and phosphorous),[2,41–46] as well as metals.[1,30]

One notable exception is Ferreira *et al.* (2008), which discusses limitations of common methods and techniques used to analyze hydrologic and erosional responses in post-wildfire settings, from laboratory to catchment scales. However, while Ferreira *et al.* (2008) does cover rainfall simulation methods, the present manuscript is the first to provide in-depth review of wildfire simulation techniques together with associated rainfall simulators. Additionally, where Ferreira *et al.* (2008) focuses on hydrologic and sedimentation impacts of fire, this review has an additional focus on postfire water quality impacts including DOM, nutrient, and heavy metal concentrations. Finally, as over a decade has passed since the Ferreira *et al.* (2008) review, the time is ripe for a fresh perspective that considers more recent research on simulation experiment techniques, drawing upon a larger pool of studies.

The studies reviewed in this paper were compiled using the search strings of "wildfire experiments", "wildfire laboratory simulations", and variations of those in the Google Scholar search engine. These were further filtered by laboratory- and/or plot-scale studies, and those which had research goals focused on hydrologic or water quality responses, as well as temperature profiles in soils. Studies examining post-fire air quality, wildfire behavior, and ecosystem restoration were excluded. From these studies, only those analyzing burn effects of natural fuels (*i.e.*, litter and woody biomass), rather than human infrastructure and anthropogenic fuels (*i.e.*, plastics and metals), were included. Additional studies were identified through the internal references across the initial set of publications. In total, 40 studies were included: 23 had a wildfire simulation component and 27 had a rainfall simulation component, with 10 studies implementing both elements.

3 Terminology

A variety of wildfire characterization terms are commonplace across studies, despite calls for standardization in recent decades.[47–50] In this review, *wildfire* is used to describe fires which occur in a natural environment, though *bushfire* is an interchangeable term common in Australia. Following are the definitions for *wildfire intensity* and *wildfire severity* as used in this review, as well as other relevant wildfire and rainfall simulation terms.

Wildfire intensity: is typically a quantitative characterization of energy, such as the amount of fuel burned (*e.g.*, units of g),[22] the rate of fuel burned (*e.g.*, units of g s^{-1} or W m^{-2}),[22,51] or peak temperature (*e.g.*, units of °C).[24,48,49,52–54] This allows for explicit quantifications of mild to severe burn intensities, however the lack of a standardized scale across studies makes cross-comparisons difficult.[2,22,55,56]

Wildfire severity: is typically a visual characterization of the response of an ecosystem (*i.e.*, vegetation, soil, water systems, and atmosphere) to fire,[5,47,50] such as ash color or amount of

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biomass consumed.[29,57] Similar to *wildfire intensity*, a standard definition of a *wildfire severity* range from low to high does not exist across studies.[38,48,58]

Laboratory-scale simulations: of wildfire and rainfall are typically applied to smaller soil samples (~0.0045–4 m^2)[26,59,60] using experimental apparati. These analyses occur either inside a laboratory or in a designated outdoor setting,[29,61,62] limiting the size of samples to the dimensions of the equipment used.

Plot-scale simulations: of wildfire and rainfall typically occur over a larger area of ground or hillslope (~0.5–300 m^2)—either undisturbed or where a natural wildfire has already occurred.[63–65] If undisturbed, a prescribed burn is typically applied to the area, then rainfall simulators used to generate runoff.[66,67] These experiments are also referred to as *field-scale* or *hillslope-scale* experiments, but in this review only the term *plot-scale* is used.

Rainfall intensity: is the ratio of the total rain depth (*e.g.*, units of mm) to the duration of rainfall (*e.g.*, units of minutes, hours, or days).

Slope: is the average topographical inclination or gradient across a terrain surface (*e.g.*, units of degrees or percent).

4 Wildfire-driven effects on water quality and supply

4.1 Sedimentation

Wildfire-driven increases in suspended sediment in streamflow have been reported from 1 to up to 1459 times pre-disturbance levels.[13] Downstream impacts of elevated sediment loading include strain on water treatment plants, reductions in reservoir storage capacity, and disruption to freshwater ecosystems.[1,11,12] Increased sediment loads can require increases in water treatment plant infrastructure and monitoring.[1,11,68] Sediment-driven reservoir filling reduces the storage capacity, limiting available water for municipalities, and is expensive to mitigate using dredging or tunnels.[69–71] Finally, increased turbidity from wildfire-driven sediment limits sunlight needed for photosynthesizing organisms that produce oxygen and form the base of aquatic food chains, resulting in fish death.[72–74]

Sedimentation is enhanced by erosional effects due to loss of vegetation (both ground and canopy cover) and root structure,[27,75,76] exacerbated by high runoff rates in post-fire settings. Rill erosion, for example, expands channel networks through high-flow rate runoff flowing through streamlets – the eroded soil mobilized into suspended sediment.[76] These high post-fire runoff rates can be driven by increased soil water repellency[75,77,78] thought to occur during heating and combustion processes in wildfires.[13,43,75,79–81] Organic compounds in litter and topsoil can be volatilized and fill the pores of upper soil layers creating water repellent effects,[29] further increased by the melting and redistribution of waxes and organic molecule polymerization.[81]

Sediment is further supplied by an accumulation of combusted vegetation and soil organic material (*i.e.*, ash), mobilized by erosional effects.[77] Initially, ash can absorb and store large amounts of rainfall (in one case, 99% for a ~15 mm precipitation storm), thereby limiting runoff generation.[79] In subsequent or larger storms when ash saturation occurs, runoff generation increases, exacerbated by increased water repellency, and ash is mobilized downstream—contributing to high sedimentation rates.[79,82]

4.2 Dissolved organic matter

Post-fire runoff DOM response varies widely across studies, from slight decreases in concentration to levels in the 95th percentile of pre-fire conditions.[1,10,13,28,43,60,83–85] Downstream, DOM is the main substrate in the formation of carcinogenic disinfection byproducts (DBPs) during the chlorination stage of water treatment.[60] Elevated levels can require water treatment plants to implement expensive alternate disinfectants, precursor (*i.e.*, DOM) and DBP removal strategies, or even force them to shut down.[84,86,87]

Alterations in the load and chemistry of DOM in post-fire settings is driven by thermal reactions during burning.[87,88] However, isolating wildfire-driven DOM response is challenging because of natural background sources of DOM, contributed by other hydrological, topographical, physicochemical, and microbiological processes.[2,56] DOM levels monotonically decrease[89] or remain the same[61] with increasing burn severity in some studies, while others report peak DOM concentrations under moderate burn severity conditions.[5,26,30,83,90] Lower DOM concentrations are frequently reported at high burn intensities, likely due to DOM vaporization (transformation of organic material into carbon dioxide and water vapor) at extreme temperatures.[6,43,89]

4.3 Nutrients

Wildfire-driven increases in the nutrients phosphorous and nitrogen have been reported up to 250 and 400 times pre-burn conditions, respectively.[1,6,13] These dramatic increases in nutrients can lead to eutrophication in aquatic ecosystems.[91] Eutrophication is a process where excess nutrients lead to accelerated growth of aquatic plants and benthic communities, but also algal blooms which produce toxins and deplete oxygen from the ecosystem.[1,91,92] These effects, in addition to the impacts of sediment discussed earlier, result in the mortality of fish and other aquatic species, as well as loss of biodiversity.[85,91,92]

Many complex mechanisms contribute to changes in nutrients in post-fire settings.[1,43,93–95] However, studies have generally shown higher rates of nitrogen concentrations after burning due to deposition and changes in chemical structure.[1,43,93] Increases in phosphorous can result from constituent transport through increased post-wildfire sedimentation rates.[68]

4.4 Heavy metals

Though heavily dependent on the nature of the forest and climatic conditions, increases in dissolved heavy metal concentrations in runoff driven by wildfires can range from 2 to at least 2500 times pre-disturbance levels.[30,96] These increases can exceed federal regulations, posing health hazards as some metals are carcinogenic or can cause anemia or heart failure.[97] Increases in magnesium are of particular concern due to

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toxicity, volatility, and persistence in the environment.[98,99] Iron, manganese, arsenic, chromium, aluminum, barium, and lead have all been observed at statistically significantly higher concentrations in post-fire runoff.[13] Moderate to high intensity fires can alter soil properties, releasing sequestered metals in organic matter which are transported downstream by high post-fire flowrates.[30,100]

5 Experimental techniques to observe and quantify post-fire impacts

The strengths of wildfire and rainfall simulation experiments are in the reduction of the logistical challenges associated with collecting *in situ* data, the ability to generate baseline pre-fire data as well as replicate samples, and to provide greater control over factors in post-fire systems.[10,13,24,29] Greater control over the timescale and number of samples collected is conducive to isolating wildfire responses from background sources.[10,38] Limitations of simulation experiments include deviation from natural conditions, *e.g.* vegetation characteristics and lateral flow paths, as well as significant differences in hydrologic and chemical processes at different scales.[7,29,67] Interpretation of results from laboratory- and plot-scale simulation experiments for catchment scale impacts should incorporate uncertainties, such as landscape heterogeneity, associated with the upscaling process. The following section will first discuss key differences in plot- *versus* laboratory-scale simulation techniques, then present the strengths and weaknesses of specific methodologies for wildfire and rainfall simulation experiments. Fig. 2 shows how laboratory-, plot-, and catchment-scale studies are related in terms of size, as well as common simulation apparati used at the laboratory and plot scales.

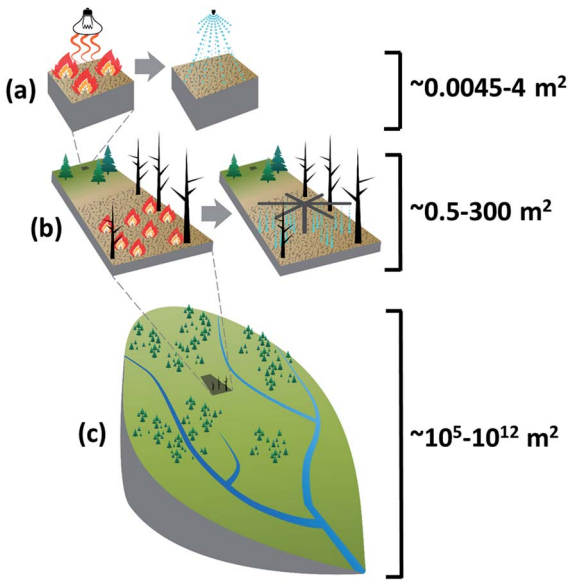

Fig. 2 Illustration of laboratory-, plot-, and catchment-scale post-wildfire study areas, with (a) a heat lamp and spray nozzle being used at the laboratory scale (~0.0045–4 m^2) for wildfire and rainfall simulation, respectively; (b) a prescribed burn and rotating-boom rainfall simulator (similar to the Swanson-style rainfall simulator[105]) being used for plot-scale (~0.5–300 m^2) wildfire and rainfall simulation, respectively; and (c) a catchment (~10^5–10^{12} m^2) affected by wildfire.

5.1 Plot- *versus* laboratory-scale simulation techniques

Plot-scale experiments are conducted on *in situ* hillslopes or plots and are generally subject to higher spatial variability in soil properties and vegetation, as well as spatial and temporal variability in burning and rainfall, than laboratory-scale experiments.[101] Though high variability can hinder the attribution of responses to drivers, this type of analysis also minimizes area-to-edge ratios (*i.e.*, limiting edge effects) and allows for larger-scale vegetation (*e.g.*, trees) and hydrologic processes to be captured.[67,76] Larger-scale hydrologic processes, *i.e.* rill formation and other erosional processes, can be key drivers of post-wildfire sedimentation and runoff responses[76] and thus important to consider in post-wildfire analyses. A wide range of replicates are typically tested in plot-scale analyses, from 0 to approximately 15.[76,102]

Laboratory-scale experiments typically use excavated, intact soil cores or homogenized samples which have low spatial variability, due in part to their smaller size.[54,67,76,89,103] Samples are typically excavated by hammering lysimeter boxes or PVC cylinders into soil[89,90] or collected from loose soil and litter on the ground—often homogenized to minimize variability.[26,54,102,104] Laboratory-scale samples are often less representative of natural conditions in terms of wildfire intensity, erosional processes, vegetation type, and soil structure, but allow for precise control over experimental factors. This is conducive to more direct attribution of the impacts of burning and other factors in the system (*e.g.*, vegetation, rainfall intensity, *etc.*) to observed responses.[29] Another key feature of laboratory-scale analyses is they allow for the measurement of infiltration through the bottom of samples and subsurface later flows, which is difficult or impossible in plot-scale *in situ* analyses.[29,90,104] A comparison of the pros and cons of plot- and laboratory-scale analyses are presented in Table 1. The number of replicate samples in laboratory-scale analyses typically range from 2–5.[56,106]

5.2 Wildfire simulation

Prescribed and slash burns, propane torches and heat lamps, litter burns, and muffle furnaces have all been used to study the effects of burning on soil and runoff physical and chemical properties.[22,26,54,67,83,90,103] The key features which differ across these techniques are the range of simulated wildfire intensities, methods of burn characterization, and spatial variability of the combustion and burn properties. These studies are tabulated in Table 2 and are described in the following sub-sections.

5.2.1 Prescribed and slash burns. Prescribed and slash burns are used as wildfire simulation techniques for plot-scale analysis of erosional, hydrologic, and sedimentation response to burning.[63,76,107] They involve the application of an incendiary device to *in situ* accumulated fuels under conditions conducive

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Table 1 Comparison of pros and cons of plot- and laboratory-scale simulation experiments based on the following factors: spatial and temporal variability, control over environmental factors, representation of natural environments, edge effects, and subsurface flows. An N/A entry indicates that no significant pro or con exists for that category

		Plot-scale (~0.5–300 m^2)		Laboratory-scale (~0.0045–4 m^2)	
		Pros	Cons	Pros	Cons
Spatial and temporal variability		Higher variability in climatic, burn, rainfall, and soil and vegetation factors similar to the natural environment	Higher variability can hinder attribution of responses to drivers	Lower variability allows for greater attribution of responses to drivers	Lower variability not as representative of the natural environment
Control over environment and experimental factors		N/A	Little control over climatic conditions and other factors in experimental environment	Precise control over climatic, burn, and rainfall factors, as well as soil and vegetation characteristics	N/A
Representation of natural environments	Wildfire intensity	Able to simulate high intensity fires	Trade-off between scale and fire intensity (*i.e.*, high intensity typically applied on smaller scales)	N/A	Typically only low to moderate intensity fires simulated
	Hydrologic and erosional processes	Allows for some larger-scale erosional processes such as rill formation	Does not capture basin-scale erosional processes such as streambed erosion	N/A	Larger-scale hydrologic processes typically not represented
	Vegetation	Larger-scale vegetation such as trees represented	N/A	N/A	Typically only small-scale vegetation represented
	Soil structure	Soil minimally disturbed or not at all	N/A	N/A	Soil structure may be compromised during excavation or purposefully homogenized
Edge effects		Minimized area-to-edge ratio	N/A	N/A	Greater edge effects
Subsurface flows		N/A	Typically does not allow for measurements of subsurface flows	Allows for the analysis of infiltration and lateral subsurface flows	N/A

to the control of a fire, *i.e.* low winds and high soil moisture.[63,66,107–110] Either aerial or ground-based incendiary devices are used to start these fires, such as a Plastic Sphere Dispenser[111] or a drip torch,[112,113] respectively. Prescribed burning, also referred to as control or experimental burns,[113,114] typically span a 40–200 ha (100–500 acre) area and most often burn at a low intensity, only consuming fuels with small diameters (*e.g.*, pine needles and small branches).[115] Slash burns, also referred to as pile burns,[115] involve first collecting surplus woody debris (*i.e.*, trees or brush) into a concentrated area – typically burning at a high intensity.[115–117] Prescribed and slash burns are most often qualitatively characterized by visual characteristics, such as biomass consumed (*i.e.*, wildfire severity).[112,118] A wide range of responses are typical for this type of technique, with runoff increasing ~20–300%, infiltration decreasing ~2–40%, sediment yield increasing ~3–200 000%, and soil chemical composition decreasing ~7–15% with burning (typically analyzed at just one burn severity increment).[63,108,113,119] However, some studies reported no statistical significance in certain results due to natural variability exceeding post-burn response.[66,119]

5.2.2 Propane torches and heat lamps. Propane torches and heat lamps are common wildfire simulation techniques used in laboratory-scale analyses of burn impacts on soil and runoff chemical composition, as well as sedimentation response and changes to soil structure.[61,90,106] These techniques involve a steady heat flux concentrated at a point (~50–100 mm) on the soil surface.[54,59,61,106,120,121] Propane torches typically produce peak soil surface temperatures of 500–600 °C [54,61] whereas heat lamps produce peak temperatures of 200–400 °C [90] from 5 to up to 220 minutes of exposure,[54,61] representing a range in burn intensities. The temperature gradient extending down through the soil surface in these experiments is typically measured using thermocouples placed 0–15 cm below the soil surface.[22,24,29,54,61,103] These studies report a wide range of significant responses to burning, with soil and water chemical constituents varying by ~10–700% and hydraulic and water repellent properties by ~60–200%, typically at 1–3 increments of burn intensities.[62,89,121] Kral *et al.* (2015) showed that propane

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Table 2 Summary of major wildfire simulation studies included in this review, listed in alphabetical order. The characteristics included are scale, size and shape of samples, wildfire simulation technique, peak burning temperature, duration of the burn, and a summary of key results from each study. The provided summaries are reported with respect to unburned conditions unless otherwise stated, *e.g.* a percent decrease indicates the percent decrease of the response after burning from the control or unburned case in the study. An N/A entry denotes an unreported study characteristic, WR is water repellency, TOC is total organic carbon, PyC is pyrogenic carbon, O horizon is organic soil horizon, Ah horizon is soil mineral horizon, KCl is potassium chloride, DOC is dissolved organic carbon, and DON is dissolved organic nitrogen

Scale	Size and shape of samples	Simulation technique	Peak burn temp	Duration of burn	Hydrologic and water quality results	Source
Laboratory	0.25 × 0.25 × 0.15 m	Propane torch or heat lamps	500 °C	~220 min	WR, TOC, PyC significantly decreased in O horizon (98, 47, 74%, respectively) WR, PyC significantly decreased in upper cm Ah horizon (74, 38%, respectively)	Badía-Villas *et al.*, 2014
Laboratory	N/A	Muffle furnace	100, 150, 200, 250, 300, 350, 400, 450, and 500 °C	5, 10, 15, and 30 min	KCl-extractable organic anion concentrations peaked between 150 and 350 °C, significantly affected by duration of heating	Blank *et al.*, 1994
Laboratory	0.3 m diam., 0.2 m height	Litter burn	230–867 °C	1–9.9 h	Soil moisture significantly affected heat transfer (>20% moisture quenched heating lower than 2.5 cm)	Busse, *et al.*, 2010
Laboratory	0.2 × 0.4 × 0.15 m	Propane torch or heat lamps	200 and 400 °C	Until temp reached, cooled afterwards	Degree hours (°C h measured during burning) were positively linearly related (R^2 = 0.966) to sum of Na, K, Ca, and Mg cations	Cancelo-Gonzalez, *et al.*, 2012
Laboratory	0.45 × 0.2 × 0.15 m	Propane torch or heat lamps	200 and 400 °C (at 1 cm depth)	Until temp reached, cooled afterwards	Leached cations increased significantly (114% and 183% in moderate and severe burns, respectively)	Cancelo-Gonzalez, *et al.*, 2013
Laboratory	0.2 × 0.4 × 0.15 m	Propane torch or heat lamps	200 and 400 °C (at 1 cm depth)	Until temp reached, cooled afterwards	Al and DOC increased 19 and 21%, respectively, for moderate burns and 44 and 679% for severe burns Fe increased only at severe burns (66%)	Cancelo-Gonzalez, *et al.*, 2015
Laboratory	N/A	Muffle furnace	225, 350, and 500 °C	2 h	DOC peaked at mild-moderate burns (84% increase) and was lowest for severe burns (99% decrease)	Cawley *et al.*, 2017
Laboratory	N/A	Muffle furnace	149, 204, 260, 316, 371, 427, and 482 °C	5, 10, 15, and 20 min	Non-wettability did not increase for mild burns, increased after 10–20 min for mild-moderate burns Impenetrability reached after 5–10 min for moderate burns,	Debano and Krammes, 1966

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Table 2 (*Contd.*)

Scale	Size and shape of samples	Simulation technique	Peak burn temp	Duration of burn	Hydrologic and water quality results	Source
					was destroyed after 10 min for severe burns	
Plot	3 × 10.7 m	Prescribed or slash burn	Low intensity	N/A	Runoff ratio and sediment yield increases (21% and 40%, respectively) were not significantly greater than natural variability	Emmerich and Cox, 1992
Plot	0.5 m^2	Prescribed or slash burn	N/A	N/A	Infiltration significantly decreased in bunchgrass, shortgrass, and oak-dominated sites (25–36%) Sediment yield significantly increased for all sites (344–225,000%)	Hester *et al.*, 1997
Laboratory	N/A	Muffle furnace/litter burn	Muffle: 200, 250, 300, 350, 400, 450, and 550 °C; flame: 520, 460, 350 °C	Muffle: 2 h; flame: 200–700 s (until 5 g, 10 g, and 25 g of fuel were incinerated)	Muffle furnace: total C, P changed monotonically with burn intensity (89% decrease and 1381% increase, respectively); total N peaked at moderate burns (385% increase), decreased at severe burns Litter burning: results showed no significant trends with burn intensity	Hogue and Inglett, 2012
Laboratory	0.5 × 0.5 × 0.05 m (+ litter layer)	Muffle furnace	225, 350, and 500 °C	2 h	DOC decreased significantly for mild-moderate burns (52%), DOC : DON non-significantly decreased27%	Hohner *et al.*, 2019
Laboratory	0.48 × 0.28 × 0.05 m	Litter burn	250–300 °C	Until litter was completely burned	WR was moderate, peak runoff rates increased up to 5525%, infiltration rates decreased up to 86%, and sedimentation rates increased	Keesstra, *et al.*, 2014
Laboratory	0.2 m diam., 0.35 m height	Propane torch or heat lamps	40–94 °C	15 min	Positive correlation ($R^2 = 0.90$) between vesicular-arbuscular mycorrhizal colonization and soil temperature	Klopatek *et al.*, 1988
Plot	N/A	Prescribed or slash burn	N/A	N/A	Infiltration rates and sediment yield decreased 2 and 3%, respectively, though not with statistical significance	Knight *et al.*, 1983
Laboratory/ Plot	2 × 2 m (burn box), 1.2 × 2.4 m (burn table)	Litter burn/Propane torch or heat lamps			Burn box, burn table, and prescribed fires had similar	Kral *et al.*, 2015

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Table 2 (*Contd.*)

Scale	Size and shape of samples	Simulation technique	Peak burn temp	Duration of burn	Hydrologic and water quality results	Source
			650 °C (prescribed); 600 °C (burn box); 400 °C (burn table); 400 °C (propane prong)	Until fuel burned (prescribed, burn box, burn table); 60 s (propane prong)	time–temperature profiles, but propane prong fires had most similar total heat dosages to prescribed fires	
Plot	1 m^2	Prescribed or slash burn	35–563 °C	Until done burning	Runoff ratios and sediment yields increased 275% and 775%, respectively	Marcos *et al.*, 2000
Laboratory/ Plot	0.1 × 0.1 × 0.1 m	Litter burn/Propane torch or heat lamps	Low intensity	N/A	Root mat soils with moisture contents of 93% and 145% had a 50% and 10% probability, respectively, of sustained smouldering	Reardon *et al.*, 2007
Laboratory	0.305 m diam.	Propane torch or heat lamps	100–150 °C, 250–300 °C, 400–500 °C	N/A	WR peaked for mild burns (moderate repellency), then decreased at moderate and severe burns (slight and no repellency, respectively)	Robichaud and Hungerford, 2000
Plot	0.83 m^2	Prescribed or slash burn	N/A	N/A	Infiltration rates for field capacity and dry conditions, respectively, significantly decreased (~11%) and did not change Sediment yields significantly increased ~141% for all conditions	Roundy *et al.*, 1978
Laboratory/ Plot	70 × 70 m (plot)	Prescribed or slash burn/ Muffle furnace	370, 470, and 570 °C (muffle furnace)	155, 105, and 65 s	PyC mass decreased 7–15% for experimental fire and 1–15%, 28–63%, and 26–37% for increasing muffle furnace temperatures	Santín *et al.*, 2013
Laboratory	0.103 m diam., 0.1 m height	Propane torch or heat lamps	600 °C	5 min	Soil moisture significantly reduced peak temperatures, duration of heating above 60 and 175 °C; rock cover reduced peak temperatures, increased heating durations	Stoof, *et al.*, 2011
Laboratory	0.2 m diam., 0.1 m height	Propane torch or heat lamps	200–250 °C, 450–500 °C	~40 min	Hydraulic conductivity significantly decreased for moderate burns (~62%), increased for severe burns (~229%) TOC significantly increased for moderate burns (~60%), decreased for severe burns (~11%)	Wieting *et al.*, 2017

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prong fires had disparate time–temperature curves compared to prescribed fires, with longer durations near peak temperatures, but the least difference in total heat dosage.

5.2.3 Litter burns. Litter burns are a laboratory-scale wildfire simulation technique used to study burn effects on soil and runoff composition, as well as the effects of soil composition on heating profiles.[29,59,103,120] The method involves igniting small amounts of litter spread evenly on top of soil samples, reaching temperatures of 230–867 °C.[29,120,122] This measured amount of fuel allows for a direct and quantitative measurement of burn intensity.[22,29] Additionally, similar to propane torches and heat lamps, thermocouples placed 0–15 cm below the soil surface are used to measure heating profiles during the burn process.[29,59,122] Study results show substantial changes in water repellency, runoff and infiltration rates (up to a ~6000% increase and ~90% decrease, respectively), and sedimentation rates,[29] as well as clear soil heating profiles, analyzed at typically 1–3 increments of burn intensities.[59,103,120] Hogue and Inglett (2012) found significant changes in some soil chemical properties (*i.e.*, total carbon and nitrogen) after litter burning, however no clear trend with increasing burn intensity was observed due to heterogeneity of burn residues. Kral *et al.* (2015) showed that litter burns had analogous time–temperature curves to prescribed fires, however often had significantly higher heat durations and dosages.

5.2.4 Muffle furnaces. Muffle furnaces are a laboratory-scale wildfire simulation technique typically used to analyze burn impacts on soil chemical composition.[26,52,113,123] Samples are placed in an oven which is typically raised to temperatures between 100-570 °C for as little as 65 seconds up to 2 hours to simulate a range of burn intensities.[26,52,83,113] Results from muffle furnace studies show generally significant monotonic and parabolic-shaped trends in leached chemical constituents and water repellency, typically measured at 1–9 increments of burn intensities.[22,26,52,83,113,123] Hogue and Inglett (2012) found that, unlike litter burns, muffle furnace burning did not produce heterogeneous burn residues – commonly observed in natural wildfires.

5.3 Comparison of key wildfire simulation technique characteristics

Each of the wildfire simulation experiment techniques described above has benefits and limitations which future researchers may take into consideration in their own designs. Table 3 shows a broad description the pros and cons of each technique.

The following paragraphs discuss common pros of wildfire simulation experiments as listed in Table 3:

Heterogeneous combustion (WP1) is a key strength of prescribed fires and slash burns, as well as litter burns. The variability in spatial distribution of heating and volatilization created by these types of burns produce variable combustion residues analogous to natural wildfires. This variability is due to spatial heterogeneity of fuel types and amounts, as well as variable wind speed, direction, and air temperature across the burn area in plot-scale experiments.[22]

Similar intensity and duration to a natural wildfire (WP2) is a strength of prescribed fires and slash burns. As a comparable amount of fuel is available in a prescribed burn as a natural wildfire, prescribed fires typically match the peak temperatures and duration of a low intensity wildfire.[112] Slash burns can reach the extreme temperatures reached by severe wildfires, sometimes as high as ~2200 °C—often unachievable by laboratory-scale simulation techniques.[117]

Precise control over burn intensity and spatial distribution (WP3) is a strength of propane torches and heat lamps, as well as litter burns.[121] This technique allows for more direct attribution of burning effects to specific intensities, given the controlled range and spatial distribution of burn intensities.[29]

Low variability in heating (WP4) is a benefit of propane torches and heat lamps, as well as muffle furnaces. Low spatial and temporal variability created by the consistent heating distribution of these methods is conducive to quantitative analysis, as it limits variability-driven uncertainty in responses.[113]

Allowance for measurement of heating profiles (WP5) is a key aspect of propane torches and heat lamps, litter burns, and muffle furnace methods. Propane torches and heat lamp methods, as well as litter burns, achieve this using thermocouples, and muffle furnaces achieve this through digital temperature readings. This allows for consistent characterization of burn intensity, conducive to quantitative post-wildfire analyses.

Control over duration of heating (WP6) is an attribute of propane torches and heat lamps, as well as muffle furnaces. This allows for further control and precision of burn intensity—sometimes characterized by burn duration.[24]

Incremental control over burn intensity (WP7) is a benefit unique to muffle furnaces. This feature allows for analysis of changing burn effects over a range of burn intensities—conducive to analyzing response trends with increasing burn intensity.[113]

The following paragraphs discuss common cons of wildfire simulation experiments as listed in Table 3:

Qualitative burn severity characterization (WC1) is a limitation for prescribed fires and slash burns.[67,101] Qualitative wildfire characterizations (*i.e.*, burn severity) are less precise than temperature or fuel measurements (*i.e.*, burn intensity), hindering quantitative analyses and precise replication of simulated burn severities.

Tradeoff between high intensities and burn coverage (WC2) is another limitation for prescribed fires and slash burns. As these burns must be managed in a safe, controlled way, larger prescribed burns (40–200 ha) are typically limited to a low burn intensity. Slash burns, which can achieve extreme temperatures, are therefore limited to smaller areas.

Uniformity in spatial heating (WC3) is considered a limitation for propane torch and heat lamp methods, as well as muffle furnaces. While this characteristic may assist in the attribution of burn effects to specific drivers, it typically does not produce the heterogeneous combustion residues present after a natural wildfire. This is a key source of uncertainty in the representativeness of burned soil structure and composition as compared to natural

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Table 3 Pros and cons of wildfire simulation techniques covered in the review, as well as the studies referenced and their scales. WP1, WP2, *etc.* represents wildfire simulation pro 1, wildfire simulation pro 2, *etc.* Similarly, WC1, WC2, *etc.* represents wildfire simulation con 1, wildfire simulation con 2, *etc*

Simulation Technique	Pros	Cons	Scale	Sources
Prescribed Fire or Slash Burn	WP1-heterogeneous combustion similar to natural wildfires WP2-similar intensity and duration as a natural wildfire	WC1-qualitative wildfire characterizations WC2-tradeoff between intensity and size of burn	Plot	Emmerich and Cox, 1992; Hester *et al.*, 1997; Marcos *et al.* 2000; Roundy *et al.*, 1978; Santin *et al.*, 2013
Propane Torch or Heat Lamp	WP3-control over burn intensity and spatial distribution WP4-low variability in heating WP5-allowance for measurement of heating profile WP6-control over duration of heating	WC3-uniformity in spatial distribution of heating	Laboratory	Badía-Villas *et al.*, 2014; Cancelo-Gonzalez, *et al.*, 2012; Cancelo-Gonzalez, *et al.*, 2013; Cancelo-Gonzalez, *et al.*, 2015; Klopatek *et al.*, 1988; Robichaud and Hungerford, 2000; Stoof *et al.*, 2011; Wieting *et al.*, 2017
Litter Burns	WP1-heterogeneous combustion similar to natural wildfires WP3-control over burn intensity and spatial distribution	WC4-limited to low-intensity burns	Laboratory	Busse, *et al.*, 2010; Keesstra, *et al.*, 2014
	WP5-allowance for measurement of heating profile		Laboratory/Plot	Kral *et al.*
Muffle Furnaces	WP4-low variability in heating WP5-allowance for measurement of heating profile WP6-control over duration of heating WP7-incremental control of burn intensity	WC3-uniformity in spatial distribution of heating WC5-heating occurs from all sides	Laboratory	Blank *et al.*, 1994; Cawley *et al.*, 2017; Debano and Krammes, 1966; Hohner *et al.*, 2019

combustion (*i.e.*, burning fuel).[22] Some studies have addressed this shortcoming by using controlled heating methods coupled with igniting vegetation or litter on the soil surface.[59,90,120]

Limitations to low-intensity burns (WC4), due to safety and other logistical considerations, is a drawback of litter burns.[103] The even distribution of fuels is often inconsequential in substantively heating soils, which may not exceed a low intensity burn.[122]

Heating from all sides (WC5) is a disadvantage of muffle furnaces. These heating mechanics are categorically different from a natural wildfire, which only heat the side of exposed soil surface.[26,52]

5.4 Rainfall simulation

Nozzle-based and drip-based rainfall simulators, water drop penetration time (WDPT) tests, and leaching are typically used in conjunction with one of the wildfire simulation techniques mentioned above or they are implemented *in situ*, over an area already burned by a wildfire.[29,78,104,105,124–126] The effects of consecutive rainfall events, with drying periods anywhere from 30 minutes to 1 year, are examined by some rainfall simulation studies, as antecedent moisture content and weathering over time can greatly influence post-wildfire hydrologic response.[10,64,79] Runoff collection chambers in these simulations are typically located at the lower end of a sloped plot or sample with a guard to deflect the simulated rainfall, with sampling frequencies ranging from 20 seconds to 20 minutes.[29,64,76,104] To facilitate discussion, various rainfall simulation techniques are divided into four categories: fixed nozzle-based simulators, dynamic nozzle-based simulators, drip-style rainfall simulators, and WDPT tests and leaching. The key features which vary between these simulation techniques are range of rainfall intensities, precision of the droplet size and kinetic energy, and spatial distribution. Published wildfire studies which employ these techniques are listed in Table 4 and described in the following subsections.

5.4.1 Fixed nozzle-based rainfall simulators. Fixed nozzle-based rainfall simulators have been used in both plot- and laboratory-scale analyses of wildfire impacts on soil and runoff physical and chemical changes.[65,90,104,127–129] Most of these simulators use a single, stationary nozzle ~2 m above the ground which points downward, covering areas of 0.08–1

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m^2.[62,108] One exception is the plot-scale Field Efficient Colorado State Rainfall Simulator which has ten 3 m risers covering 300 m^2, each with 1–2 nozzles pointing upwards.[65,130] Nozzles are rated to produce a droplet size and kinetic energy similar to natural rainfall at a specified distance beneath the nozzle, as well as an even distribution of rainfall intensity (*e.g.*, the Full-Jet® and VeeJet© nozzles produced by the Spraying Systems Company).[104,127,129] Droplet sizes range from 0.8–4.0 mm and kinetic energies from 0.1–28 J m^{-2} mm^{-1}, with rainfall intensities ranging from 5–203 mm h^{-1} and durations from 5 min to 2 h.[90,108,127–129,131,132] Results from studies which implemented this type of simulator show a wide range of significant responses in runoff solute concentrations (~20–700% increases), runoff (~10–20 000% increases), and sediment (~300–20 000% increases) after burning, typically measured at 1–3 increments of rainfall intensities.[62,65,90,102,126] However, some studies also reported little statistical significance in runoff and infiltration rate response.[65]

5.4.2 Dynamic nozzle-based rainfall simulators. Although dynamic nozzle-based rainfall simulators have been used to analyze similar wildfire effects as fixed nozzle simulators, their use is more common in plot-scale analyses.[64,66,76,78,101,105,133] These simulators incorporate horizontal rotation[29,105] or sweeping motions ~3 m above the plot or samples,[76,78,101,134] covering large areas of up to ~30 m^2.[66] The nozzles used are rated to produce natural rainfall kinetic energy and droplet size, same as the fixed nozzle simulators, and produce rainfall intensities ranging from 33–127 mm h^{-1} for 15 min up to 4 hours.[105] Studies with this type of simulator report wide ranges of generally significant responses in runoff (~5–600% increases), infiltration (~30–90% decreases), and sediment (~40–7000% increases) after burning, analyzed at 1–2 increments of rainfall intensities.[29,64,66,76,78,82,133] Studies analyzing responses several months or years after burn events tended to not see significance in results.[66,76,78,82,133]

5.4.3 Drip-style rainfall simulators. Drip-style rainfall simulators have been used to study the same processes as nozzle-style simulators, typically at a plot-scale.[63,124,135] In these simulators, water is channelled to a large number (~168 to 2209) of fine tubes or needles which periodically release droplets due to gravitational forces,[125,135] covering areas from 0.4–9 m^2.[119,135,136] This technique produces droplet sizes ranging from 2.6–3.3 mm in diameter and rainfall intensities ranging from 20–203 mm h^{-1} (ref. 63 and 124) for durations of 0.5–1 hour.[133,136] Results from studies using this type of simulation technique show generally significant changes in runoff chemical constituents (~20–49% increases),[124] as well as infiltration rates (~2–11% decreases) and sedimentation rates (~3–300 000% increases) after burning, typically analyzed at 1–3 rainfall intensity increments.[63,119,136]

5.4.4 Water drop penetration time tests and leaching. WDPT tests and leaching do not simulate the mechanics of rainfall, but are important laboratory-scale techniques used to assess wildfire impacts on soil water repellency and changes in chemical composition, respectively.[52,61,83,89,123] WDPTs involve placing droplets of water or a water–ethanol mixture on burned soil and recording the duration of time for each drop to infiltrate as a measure of soil water repellency.[61,121,137] Leaching involves dissolving water-soluble chemical constituents in burned soil or litter into water, then analyzing the water for chemical composition.[26] Studies which used this type of analysis show generally significant changes after burning in water repellency and hydraulic conductivity (~60–200% increases), as well as leached chemical constituents (~10–60% increases and decreases).[29,89]

5.5 Comparison of key rainfall simulation technique characteristics

The rainfall simulation techniques described above all have benefits and limitations which future researchers may take into consideration. Table 5 shows a broad description the pros and cons of each technique.

The following paragraphs discuss common pros of rainfall simulation experiments as listed in Table 5:

Simplicity in design (RP1) is a key benefit of fixed nozzle-based rainfall simulators, WDPT tests, and leaching.[90,127,129,130] A stationary nozzle is a relatively simple and inexpensive mechanism to construct or purchase, and is often sufficient in terms of coverage area and semblance to natural rainfall. WDPT tests and leaching typically only require simple laboratory equipment.

Transportability and adaptability to steep terrains (RP2) is a benefit of fixed nozzle-based rainfall simulators. This allows these simulators to be tested on otherwise inaccessible sampling locations and on steep terrains up to 45°.[65,127,129]

Rainfall intensities and droplet sizes similar to natural rainfall (RP3) is a key benefit of fixed nozzle-based, dynamic nozzle-based, and drip-style rainfall simulators. The ranges of intensities and droplet sizes for these types of simulators make them representative of typical natural precipitation.[90,108,127–129]

A large area of coverage (RP4) is a benefit unique to dynamic nozzle-based rainfall simulators. Larger plot-scale analyses allow for larger-scale hydrologic processes to occur which cannot be observed on smaller scales,[138–140] and minimizes edge effects.[67]

Spatial and temporal variability in droplet distribution similar to natural rainfall (RP5) is an important attribute of dynamic nozzle-based rainfall simulators. The horizontal rotation and sweeping motion of the nozzles used in these simulators may create spatial and temporal variability which is more representative of natural rainfall than stationary nozzles.[125]

Increased control and precision of droplet size (RP6) is a benefit of drip-style rainfall simulators. Droplet size can be altered by changing the gage of the tubes and needles used, allowing for control over droplet diameters[125] and subsequently the kinetic energy of raindrops produced.

Direct measurement of water repellency and chemical changes (RP7) is a benefit unique to WDPT tests and leaching. This can allow for more precise attribution of burn effects, as opposed to the indirect measurements through runoff generation and chemical composition in other rainfall simulation techniques.[26,89,123]

The following paragraphs discuss common cons of rainfall simulation experiments as listed in Table 5:

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Table 4 Summary of major rainfall simulation studies included in this review, listed in alphabetical order. The characteristics included are study subject, scale, size and shape of samples, rainfall simulation technique, rainfall intensity, duration and scheduling of the simulated rainfall, and a summary of key results from each study. The provided summaries are reported with respect to unburned conditions unless otherwise stated, *e.g.* a percent decrease indicates the percent decrease of the response after burning from the control or unburned case in the study. An N/A entry denotes an unreported study characteristic. WR is water repellency, TOC is total organic carbon, and DOC is dissolved organic carbon

Scale	Size and shape of samples	Simulation technique	Rate of rainfall	Duration and schedule of rainfall and drying	Hydrologic and water quality results	Source
Plot	1 m^2 plots	Dynamic nozzle-based	79 mm h^{-1}	1 h	Runoff ratios peaked immediately post-fire (5 and 20% increases for moderate and severe burns, respectively), muted effects from older fires Sediment yield peaked for 1 year old fires (485% and 2392% increases for moderate and severe burns, respectively)	Benavides-Solorio and MacDonald, 2001
Plot	N/A	Dynamic nozzle-based	N/A	N/A	N/A	Bertrand, 1961
Plot	3 × 3 m	Drip-style	5.1–83.8 mm h^{-1}	N/A	N/A	Blackburn *et al.*, 1974
Plot	1 × 0.5 m	Drip-style	20, 40, and 60 mm h^{-1}	Until three temporally discrete runoff samples had been collected	Total P increased 20% and 49% for moderate and severe burns, respectively Suspended sediment increased 323% and 717% for moderate and severe burns, respectively	Blake *et al.*, 2010
Laboratory	0.2 × 0.4 × 0.15 m	Fixed nozzle-based	N/A	N/A	Degree hours (°C hrs measured during burning) were positively linearly related ($R^2 = 0.966$) to sum of Na, K, Ca, and Mg cations	Cancelo-Gonzalez, *et al.*, 2012
Laboratory	0.45 × 0.2 × 15 m	Fixed nozzle-based	75 mm h^{-1}	Runoff collected in 300 mL aliquots. 3 sessions, 2 h long, 15 days apart	Leached cations increased significantly (114% and 183% in moderate and severe burns, respectively)	Cancelo-Gonzalez, *et al.*, 2013
Laboratory	0.2 × 0.4 × 0.15 m	Fixed nozzle-based	75 mm h^{-1}	Runoff collected in 300 mL aliquots. 300 mm per session, 2 sessions, 2 h long, 15 days apart	Al and DOC increased 19 and 21%, respectively, for moderate burns and 44 and 679% for severe burns Fe increased only at severe burns (66%)	Cancelo-Gonzalez, *et al.*, 2015
Plot	0.24 m^2	Fixed nozzle-based	54.6 mm h^{-1}	N/A	N/A	Cerda *et al.*, 1997
Laboratory	Potted plants	Drip-style	6.5, 8.5, and 9.9 mm h^{-1}	1 h	N/A	Chevone *et al.*, 1984
Plot	3 × 10.7 m	Dynamic nozzle-based	55 and 110 mm h^{-1}	45 and 15 min	Runoff ratio and sediment yield increases (21% and 40%, respectively) were not significantly greater than natural variability	Emmerich and Cox, 1992
Plot		Fixed nozzle-based	50.5 mm h^{-1}	45–60 min		Ferreira *et al.*, 2005

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Table 4 (*Contd.*)

Scale	Size and shape of samples	Simulation technique	Rate of rainfall	Duration and schedule of rainfall and drying	Hydrologic and water quality results	Source
	0.24 m^2 (microplot), 8 × 2 m (plot), and <1.5 km^2 (catchment)				Runoff ratios increased 343, 614, and 1746% for mild, moderate, and severe burns, respectively, for micro-plot scale; increased 14 and 16,471% for mild and severe burns, respectively, for plot scale	
Plot	0.5 m^2	Drip-style	203 mm h^{-1}	50 min	Infiltration significantly decreased in bunchgrass, shortgrass, and oak-dominated sites (25–36%) Sediment yield significantly increased for all sites (344–225 000%)	Hester *et al.*, 1997
Plot	N/A	Fixed nozzle-based	N/A	N/A	N/A	Holland, 1969
Plot	3.03 × 10.7 m	Dynamic nozzle-based	60 mm h^{-1}	1 h event, 24 h drying period, 0.5 h event, 0.5 h drying period, 0.5 h event	Runoff ratios and sediment yields increased 103% and 2240%, respectively	Johansen, *et al.*, 2001
Laboratory	0.48 × 0.28 × 0.05 m	Dynamic nozzle-based/ WDPT tests and leaching	33 mm h^{-1}	4 h event, drying period in oven, then second 2 h wetting phase	WR was moderate, peak runoff rates increased up to 5525%, infiltration rates decreased up to 86%, and sedimentation rates increased	Keesstra *et al.*, 2014
Laboratory	1 × 0.2 × 0.075 m	Fixed nozzle-based	31.7 mm h^{-1}	40 min	N/A	Kibet, *et al.*, 2014
Plot	N/A	Drip-style	203 mm h^{-1}	30 min	Infiltration rates and sediment yield decreased 2% and 3%, respectively, though not with statistical significance	Knight *et al.*, 1983
Plot	1 m^2	Fixed nozzle-based	180 mm h^{-1}	5 min	Runoff ratios and sediment yields increased 275% and 775%, respectively	Marcos *et al.*, 2000
Plot	0.75 × 0.75 m	Dynamic nozzle-based	100 mm h^{-1}	1 h (three events, each 1 year apart)	Runoff ratios increased 21% immediately post-fire, lesser values in years 1–5 Infiltration decreased 30% immediately post-fire, greater values in years 1–5 Sediment yield peaked 1 year post-fire (7227% increase), lesser values in years 0, 2, and 5	Robichaud *et al.*, 2016
Plot	4 × 8 m	Fixed nozzle-based	76 mm h^{-1}	1 h (three events, the second a couple days after first event, then the third 2 h after the second)	Runoff ratio and sedimentation rates increased ~4000 and ~17 000%, respectively, less for higher antecedent moisture contents	Rosso *et al.*, 2007

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Table 4 (*Contd.*)

Scale	Size and shape of samples	Simulation technique	Rate of rainfall	Duration and schedule of rainfall and drying	Hydrologic and water quality results	Source
Plot	0.83 m^2	Drip-style	83.8 mm h^{-1}	1 h	Infiltration rates, for field capacity and dry conditions, respectively, significantly decreased (~11%) and did not change Sediment yields significantly increased ~141% for all conditions	Roundy *et al.*, 1978
Plot	10.7 × 3.05 m	Dynamic nozzle-based	N/A	1 h, then 30 min 24 h later, then 30 min immediately	Runoff ratios and sediment yields increased 432 and 845%, respectively, immediately post-fire, 391 and 690% 1 year post-fire for severe burns; little substantial changes for mild burns	Simanton *et al.*, 1986
Plot	N/A	Dynamic nozzle-based	63.5 and 127 mm h^{-1}	N/A	N/A	Swanson, 1965
Laboratory	0.2 m diam., 0.1 m height	Fixed nozzle-based/ WDPT tests and leaching	25 mm h^{-1}	1 h	Hydraulic conductivity significantly decreased for moderate burns (~62%), increased for severe burns (~229%) TOC significantly increased for moderate burns (~60%), decreased for severe burns (~11%)	Wieting *et al.*, 2017
Plot	1 m^2	Fixed nozzle-based	69–202.5 mm h^{-1}	N/A	N/A	Wilcox *et al.*, 1986
Plot	15 × 20 m	Fixed nozzle-based	35, 75, and 150 mm h^{-1}	10–49 min	Peak runoff rates and infiltration had no substantial change Sediment yield increased 730–353%	Wilson, 1999
Plot	0.5 m^2 plots	Dynamic nozzle-based	75 mm h^{-1}	1 h events	With respect to removal of ash: Runoff ratios and infiltration increased 180% and decreased 32% 1 month post-burn, respectively; no change 12 months post-burn	Woods and Balfour, 2008

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A small area of coverage (RC1) is a limitation of many fixed nozzle-based rainfall simulators, WDPT tests, and leaching.[127] The smaller area covered limits analyses to the laboratory- or smaller plot-scale for fixed nozzle-based rainfall simulators, and typically only laboratory-scale samples for WDPT tests and leaching. This often means that these simulation experiments do not capture larger-scale hydrologic processes, such as rill erosion (as discussed in Section 5.1).

Rainfall kinetic energies lower than typical natural rainfall (RC2) is a limitation for fixed nozzle-based rainfall simulators. Rainfall kinetic energies for these simulators tend to be lower than natural rainfall due to simulated droplets often not reaching terminal velocity before impact, as nozzle heights are constrained by equipment.[127]

Complexity and expense of design (RC3) are limitations for dynamic nozzle-based rainfall simulators and drip-style rainfall simulators, which may result in logistical and financial challenges for studies.

Difficulty in transportation (RC4) is another drawback for dynamic nozzle-based rainfall simulators and drip-style rainfall simulators. This can limit plot-scale study sites to ones with accessible roads, as well as relatively flat terrain.

Lack of rainfall impact on soils (RC5), and therefore lack of droplet kinetic energy, is a limitation of WDPT tests and leaching. These methods do not capture the physical processes of rainfall impact on soil surface and therefore cannot simulate natural constituent transport through runoff.[26]

Table 5 Pros and cons of rainfall simulation techniques covered in the review, as well as the studies referenced and their scales. RP1, RP2, *etc.* represents rainfall simulation pro 1, rainfall simulation pro 2, *etc.* Similarly, RC1, RC2, *etc.* represents rainfall simulation con 1, rainfall simulation con 2, *etc*

Simulation Technique	Pros	Cons	Scale	Sources
Fixed Nozzle-Based Rainfall Simulators	RP1-simplicity in design RP2-transportability and adaptability to steep terrains	RC1-small area of coverage RC2-rain kinetic energies lower than natural rain	Laboratory	Cancelo-Gonzalez, *et al.*, 2012; Cancelo-Gonzalez, *et al.*, 2013; Cancelo-Gonzalez, *et al.*, 2015; Kibet, *et al.*, 2014
	RP3-intensities and droplet sizes similar to natural rainfall		Plot	Cerda *et al.*, 1997; ferreira *et al.*, 2005; Holland, 1969; Marcos *et al.*, 2000; Rosso *et al.*, 2007; Wilcox *et al.*, 1986; Wilson, 1999
Dynamic Nozzle-Based Rainfall Simulators	RP3-intensities and droplet sizes similar to natural rainfall	RC3-complexity and expense of design	Laboratory	Keesstra *et al.*, 2014;
	RP4-large area of coverage RP5-variability in droplet dist. similar to natural rainfall	RC4-difficulty in transportation	Plot	Benavides-Solorio and MacDonald, 2001; Emmerich and Cox, 1992; Johansen, *et al.*, 2001; Robichaud *et al.*, 2016; Simanton *et al.*, 1986; Swanson, 1965; Woods and balfour, 2008; betrand, 1961
Drip-Style Rainfall Simulators	RP3-intensities and droplet sizes similar to natural rainfall	RC3-complexity and expense of design	Laboratory	Chevone *et al.*, 1984
	RP6-increased precision in droplet size	RC4-difficulty in transportation	Plot	Blackburn *et al.*, 1974; blake *et al.*, 2010; Chevone *et al.*, 1984; Hester *et al.*, 1997; Knight *et al.*, 1983; Roundy *et al.*, 1978
WDPT Tests or Leaching	RP1-Simplicity in design	RC1-small area of coverage	Laboratory	Badía-Villas *et al.*, 2014; blank *et al.*, 1994; Cawley *et al.*, 2017; Debano and Krammes, 1966; Hogue and inglett, 2012; Hohner *et al.*, 2019; Robichaud and Hungerford, 2000; Wang *et al.*, 2015; Wieting *et al.*, 2017
	RP7-direct measurement of water repellency and quality	RC5-No rainfall impact on soil surface		

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6 Recommendations for future study design

Decisions about which experimental methodologies to choose should largely depend on study scope: the hydrologic or chemical responses being analyzed, as well as the temporal and physical scales of the analysis. Researchers should also carefully consider the geographical setting of their study and incorporate specific regional characteristics into their experimental design, such as soil type, vegetation cover, climate regimes, and terrain slopes. In general, we recommend that experimental design elements should be optimized based on their strengths in analyzing important study elements, while weighing time, logistic, and financial constraints.

For example, a study analyzing the effects of different vegetation types on post-wildfire hydrologic processes may want to focus on plot-scale techniques in order to capture larger-scale erosional processes such as rill erosion. In such a scenario, a prescribed burn method could provide the necessary burning scale, burn the intended fuel type (*i.e.*, the different types of vegetation in question), and also partially represent heterogeneous combustion patterns, intact soil structure, and larger-scale vegetation present in a natural wildfire. In this example, a dynamic nozzle-based rainfall simulator may be the best choice of rainfall simulator to allow for a large area of coverage. Alternatively, if the interaction between burn intensity and vegetation characteristics was of primary interest in the above example, then a more appropriate experimental set-up may use a burn simulation technique which allows for greater incremental control over wildfire intensity. Heat lamps, for example, allow for analysis of targeted vegetation burning at specific intensity levels. However, this type of analysis sacrifices some representation of natural burning, due to low spatial variability in combustion. Additionally, as with any laboratory method, the soil sampling process involved in heat lamp simulation techniques introduces edge effects, potentially disturbed soil structure, and can only represent small-scale hydrologic processes and vegetation. A fixed nozzle-based rainfall simulator may be the best choice in this scenario, as only a small area of coverage would be required.

Researchers should also take the results from previous simulation studies into consideration for their study designs. For example, plot-scale studies in this review which implemented prescribed burning tended to most frequently produce results that were not statistically significant relative to control samples. This is likely due to a combination of the spatial heterogeneity of burn intensities in prescribed burning methods and the high variability of plot-scale natural settings typically subjected to prescribed burning. Conversely, laboratory-scale studies which used muffle furnace heating tended to produce results that were highly statistically significant and were able to assess responses at a high number (up to nine) of burn intensity increments. This level of granularity allowed these studies to infer a more fundamental character of the heating effect, for example a monotonic *versus* negative parabolic response to heating. However, these types of analyses were typically limited to water quality constituents and water repellency, as larger-scale erosional and hydrologic responses were not captured.

Using precedents set by previous simulation studies as a guide, researchers may choose appropriate methods to fit their research goals. To aid discussion, we categorize strengths and weaknesses of simulation experiments into four important factors: (1) representation of natural processes and settings, (2) analysis of multiple post-wildfire water quality and supply drivers simultaneously and independently, (3) observation of responses on different temporal and spatial scales, and (4) mitigation of uncertainty of results. The following paragraphs discuss the tradeoffs that exist between these four key design factors.

6.1 Representation of natural processes

Replicating natural processes improves the representativeness of experimental results—furthering understanding of wildfire effects on soil and runoff characteristics. However, this goal must be weighed against logistical challenges of *in situ* collection, as well as the increased spatial and temporal variability inherent with natural features—which can create difficulties in attribution. Studies typically address these tradeoffs by only choosing natural or unperturbed features most important to the subject and scale of the study. For example, Hogue and Inglett (2012) examined carbon and nitrogen concentrations in naturally combusted residue, using litter burning with spatially variable combustion to replicate natural wildfire mechanisms.[22] Similarly, Benavides-Solorio and MacDonald (2005) and Johansen *et al.* (2001) analyzed wildfire's role in increased rill erosion, a plot-scale erosional process, by employing plot-scale wildfire and rainfall simulation techniques. Therefore, future studies are recommended to first identify the subject and scale(s) of greatest interest, then focus efforts on replicating natural processes for those elements.

6.2 Incorporation of multiple key drivers

Incorporation of multiple drivers—*i.e.* burn severity, rainfall intensity, terrain slope, vegetation type, and soil characteristics—at multiple increments and categories, is often sought to gain a more comprehensive understanding of their relative importance and system interactions. However, studies must evaluate the benefits of including these characteristics, since they can limit the number of replicate samples useful for characterizing uncertainty, as well as require large numbers of samples to be collected. Most studies in this review include burn severity and rainfall intensity in their analyses.[7,13,38,79,90] Soil structure and composition, terrain slope, climate, vegetation type, and antecedent moisture content are less commonly incorporated, but can have comparable impacts on hydrology and water quality.[93] For example, Johansen *et al.* (2001) incorporated the percentage of bare soil into their analysis of post-wildfire sedimentation, finding that this driver had a strong correlation with sediment generation in addition to burn severity. Factors involved in wildfire prevention, suppression, and mitigation of effects (*i.e.*, mechanical thinning, mulching,

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and chemical fire-retardants) are also less commonly incorporated, though could provide insights important to fire management efforts. Understanding how each driver impacts hydrology and water quality independently and jointly can also assist in the creation of catchment-scale predictive models, which typically incorporate multiple drivers as model parameters. Benavides-Solorio and MacDonald (2005), for example, used fire severity, percent bare soil, rainfall erosivity, soil water repellency, and soil texture as model parameters to predict post-wildfire sedimentation.

Responses systematically tested over ranges of drivers allows for an understanding of the shape of the response function (*e.g.*, monotonic, parabolic, *etc.*). Studies typically use only ~2–3 increments of burn severity and rainfall intensity due to logistical and time constraints.[83,90,121,124] However, a higher number of increments proved to be important in Hohner *et al.* (2019). Here, soil samples were heated in a muffle furnace at five temperature increments ranging from 150–550 °C, finding that water extractable organic carbon and nitrogen had a roughly negative parabolic relationship with temperature, peaking around 250–350 °C.[26] We recommend that for a given number of total samples, future studies carefully consider the tradeoffs between the number of increments and the number of replicates.

6.3 Analyses at multiple spatial scales

A limitation of single-scale wildfire and rainfall simulation experiments is the lack of consideration for how properties and processes at one scale may effect water quality and supply responses at larger scales.[67] Incorporating multiple physical scales in simulation experiments can provide insight into upscaling operators which can inform catchment-scale predictions. This is particularly important in sedimentation analyses, as geomorphic and erosional processes vary greatly from the laboratory-scale to the catchment-scale.[27] Post-fire sedimentation mechanisms such as streambed erosion may be entirely missing, even from plot-scale analyses. However, understanding how mechanisms (*e.g.*, rill erosion, streambed erosion, *etc.*) are introduced and change at increasing scales can allow for indirect estimation and inference about catchment-scale response.

Simulating multiple physical scales is challenging in a laboratory setting due to fixed equipment size.[29,89,90,106,122] Multi-scale analysis is also uncommon in plot-scale studies. However, Ferreira *et al.* (2005) analyzed sediment and runoff in post-fire plots on a microplot- (<1 m^2), plot- (16 m^2), and catchment-scale (<1.5 km^2), allowing for comparison of results across varying scales. We recommend that future studies consider analyzing post-fire responses at more than one scale, if feasible with their study design and logistical and financial limitations.

6.4 Uncertainty quantification

Uncertainty is most commonly estimated in experimental systems by testing multiple replicate samples, or uniform samples tested under the same conditions.[29,80] Quantifying uncertainty can be useful in differentiating the water quality responses of different drivers and can help inform upscaling of results to the catchment scale.[141,142] High spatial and temporal variability, albeit representative of natural systems, can introduce additional uncertainty due to difficulties in the attribution of responses to specific drivers. Thus, uncertainty analysis and mitigation efforts must consider both replicate uncertainty, as well as the role of natural variability on attribution uncertainty. In Keesstra *et al.* (2014), for example, soil samples were homogenized—reducing uncertainty from spatially variable soil structure and vegetation, but decreasing the samples' semblance of a natural environment. We recommend opting for greater numbers of replicate samples to quantify uncertainty, while weighing incorporation of multiple drivers at different increments and scales—which may constrain the feasible number of replicates across each study dimension.

7 Conclusion

This review provides a synthesis of knowledge on wildfire and rainfall simulation techniques used to understand the impacts of wildfire on water quality and supply. Wildfire and rainfall simulation techniques offer solutions to logistical challenges faced in the collection of *in situ* data, including potentially dangerous post-fire environments, expensive fieldwork expeditions, and lack of control data. However, each technique has unique strengths and weaknesses. Plot-scale analyses are often able to capture a higher spatial variability more representative of natural settings than laboratory-scale analyses, as well as simulate larger-scale hydrologic processes (*i.e.*, erosion). Yet, attribution of responses to specific drivers is often difficult due to high variability of conditions within and across plots.

Laboratory-scale analyses can more precisely control factors in the simulated system, limiting variability and allowing for drivers to be tested at a range of increments. This allows for a more direct attribution of the role of each driver on system responses, independently and jointly across ranges of values. Laboratory-scale experiments also have the benefit of more precise measurements (*e.g.*, using thermocouples to measure temperature profiles) and control over drivers (*e.g.*, muffle furnaces which can be set to exact temperatures for exact durations), which assists in the quantitative analysis of results. The downsides of laboratory-scale experiments are that they are less representative of a natural wildfire system, due to limited spatial variability and scale—meaning only small-scale hydrologic processes can be analyzed.

Common design considerations across these studies include representation of natural processes, incorporation of multiple key drivers, analysis at multiple spatial scales, and uncertainty quantification. As studies are limited by time, resources, and logistical constraints, prioritization of these design considerations in future studies must be made based on scale, scope, and subject matter. Representation of natural processes can increase variability, and therefore increase uncertainty in results. Similarly, increased complexities in the study design, such as incorporation of multiple drivers and spatial scales, can decrease the amount of replicate samples at each condition, thereby limiting a robust quantification of uncertainty. Thus, future studies must weigh which design considerations are important for each aspect of their experiment, focusing

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resources on realistic representation of the key drivers or constituents of interest.

This review seeks to support the advancement of knowledge in the field of wildfire impacts on water quality and supply. These findings may be informative for future practitioners, as well as for water management efforts in mitigation and adaptation strategies for wildfire impacts. As wildfires continue to represent an increasing threat to water quality and supply, developing advanced techniques to provide further understanding of wildfire effects will become increasingly essential.

Author contributions

Carli Brucker: conceptualization, writing—original draft, writing—review and editing. Ben Livneh: conceptualization, writing—review and editing. J. Toby Minear: conceptualization, writing—review and editing. Fernando L. Rosario-Ortiz: conceptualization, writing—review and editing.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This work is supported by funding through the U.S. Environmental Protection Agency, the Cooperative Institute for Research in Environmental Sciences (CIRES) Graduate Student Research Award, part of the NOAA Cooperative Agreement with CIRES, NA17OAR4320101, the 2020 CIRES Innovative Research Program, and the Western Water Assessment, NA21OAR4310309. The authors acknowledge Dr Fangfang Yao, for providing proofreading assistance and Aaron Heldmyer, for assistance in compiling literature.

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