Title: Fire and water: contaminants and clearance following uncontrolled fires

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Abstract

There is a growing body of evidence surrounding the implications of uncontrolled bushfires and wildfires on water. This topic has importance from an ecological perspective, and significance for human health as it has consequences for drinking water quality and supply. Against the backdrop of climate change, it is especially important to holistically understand the impact of fire on water. This review took a systematic approach to establish a comprehensive overview of the changes occurring in freshwater systems following uncontrolled wildfires and bushfires. Screening of 16,551 results obtained from Web of Science, PubMed, and MEDLINE resulted in 111 manuscripts suitable for inclusion. The impact of fire across a wide range of water quality indicators either relative to pre-fire measurements or reference sites was examined qualitatively (increase/decrease) and where possible quantitatively (% change or difference). Factors included biomass, indicator species and species diversity, metals, nutrients, salts, polycyclic aromatic hydrocarbons, particulates and turbidity, pH, conductivity, temperature, and water course morphology. Evidence focused largely on short to medium term impacts (e.g. within 2 years of the fire event), with only a subset of studies reporting on longer term changes in response to fire. We found that bushfire has acute and long-lasting effects on water in terms of physical (e.g. decreased suspended particle size), chemical (e.g. increased nutrient concentration), and biological (e.g. decreased species diversity) characteristics. There was also evidence of resilience and recovery. We urge future work to consider measures that will fulfil both environmental and human health considerations, to allow more integrated insight into the impacts of fire on water.

Introduction

Bushfires[1] are one of the most common and destructive natural disasters, particularly in Australia (Sharples et al., 2016). The WHO estimates that bushfires have negatively affected 6.2 million people between the years of 1998 and 2017[2]. Bushfires damage the land, and can lead to loss of life and damage to infrastructure (Sharples et al., 2016). The impact of fire and its consequences on water quality have historically received comparatively less attention than work focusing on its impact on plants and animals (Bowman & Boggs, 2006), but is growing in prominence, particularly as water managers recognise the impact fire can have on drinking water supply (Bixby et al., 2015). Broadly, fires can volatilise hazardous material from containment or pipeline infrastructure itself (e.g. as in Proctor, Lee, Yu, Shah, and Whelton (2020)), change the chemical and physical make-up of water in natural systems (e.g. as in (I. White et al., 2006)), or affect hydrological and hydrogeological factors in ways that can disrupt water supply (e.g. as in (Hallema et al., 2018)). Between extreme weather events, changes in fire management practice, and the ongoing problem of deliberate arson (the latter accounts for up to half of all bushfires in Australia (Willis, 2005)), the risk of water contamination following bushfires is an ongoing and increasing concern (Lane, Feikema, Sherwin, Peel, & Freebairn, 2010; Nunes et al., 2018; Pachauri et al., 2014).

Evidence indicates a warmer, drier climate is be linked with repeated fire events (Bixby et al., 2015; Dowdy & Mills, 2012; Hess, Scott, Hufford, & Fleming, 2001; Price & Rind, 1994; Veraverbeke et al., 2017). Anthropogenic climate change is a contributing cause of increase in fire activity. Warmer weather and an increase in lightning strikes during “dry” thunderstorms in Alaska has been linked with increasing fire severity (Hess et al., 2001), and there is evidence in North American boreal forests that lightning fire ignitions are increasingly common (Veraverbeke et al., 2017). Climate-related changes in fire frequency and extent have been linked with impacts on surface water (Holloway et al., 2020).

Not all anthropogenic fires are harmful to the landscape; historical and current practice gives many examples of indigenous peoples using fire for sustainable land management around the world (e.g. (Mistry et al., 2005; Nikolakis & Roberts, 2020; Sayre, 2007)). Many commentaries note changes in fire dynamics following shifts in governance that lead to a suppression of these traditional practices (e.g. (Nikolakis & Roberts, 2020; Sayre, 2007)). For example, in Australia, it is widely noted that disruptions to ancient cultural burning practice

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[1] The term “bushfire” connotes an Australian context, for the purposes of consistency it will be used in place of the synonymous “wildfire” or other terms connoting large (typically uncontrolled) fires burning in a natural area per WHO terminology for the remainder of this review.

[2] https://www.who.int/health-topics/wildfires#tab=tab_1

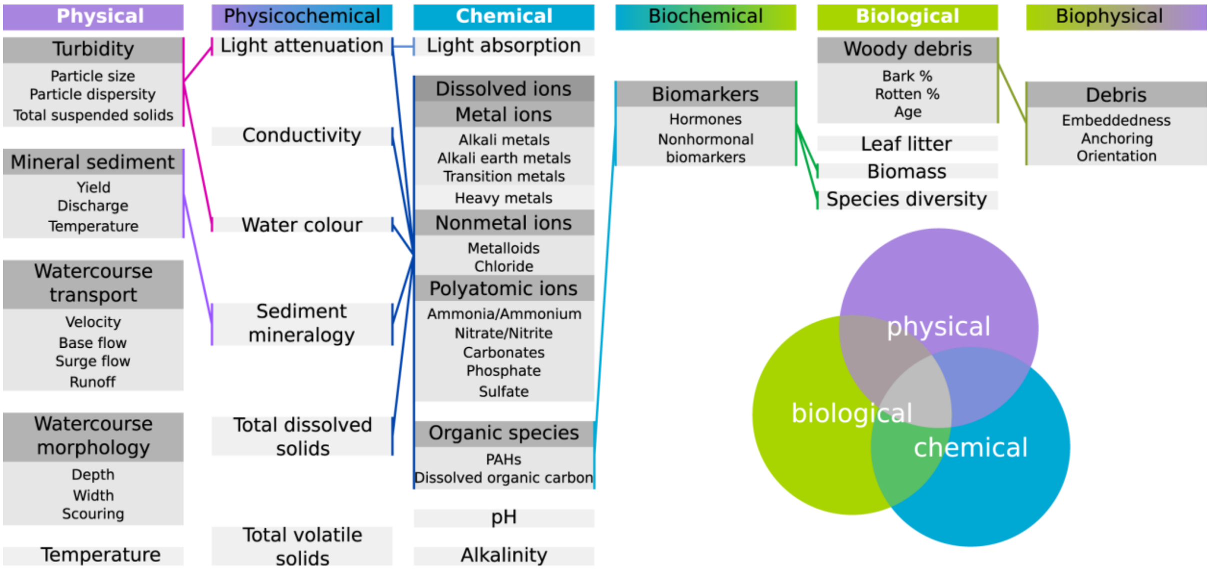
coupled with climate change have led to markedly different patterns of fire severity and occurrence in the past 250 years (Chester, 2020; Fletcher, Hall, & Alexandra, 2020; Lane et al., 2010).

The fire history of a landscape is the extent, severity, intensity, frequency, type (controlled/prescribed versus uncontrolled) of fires, and the characteristics of that landscape such as slopes, soil type, vegetation, and the geomorphology of watersheds and the bodies of water themselves (Bixby et al., 2015). Against this historical backdrop, the impacts of fire are embedded in the complex interaction within and between physical, chemical, and biological factors. The following sections provide a brief introduction to the focal factors covered in this review, highlighting salient interactions to bring context to results. In the interest of brevity, we have also prepared a figure based on additional literature summarising inter-relationships in more detail (see Figure 1).

Review approach and aim

The aim of this review was to establish a comprehensive overview of the current state of evidence regarding changes occurring in fresh waterways following bushfires. This review builds on groundwork such as Bixby et al.'s overview of the impact of fire on stream ecosystems (see Figure 1, p1341 of ((Bixby et al., 2015)). It joins large, in-depth reviews such as Smith, Sheridan, Lane, Nyman, and Haydon (2011)'s narrative review on fire effects on water quality in forest catchments, and the study of the impact of fire on a single site, Earl and Blinn (2003)'s exploration of the impact of ash on Gila River drainage. We take a systematic approach and expand the breadth of indicators to explicitly include the hydrological and geomorphological effects of fire on water.

Figure 1. Schematic of associations and interactions between factors discussed in this review, per existing literature



Note: In this review, evidence for each factor is explored individually under the three major headings of physical, biological, and chemical. It is important to recognise that these sections, and factors within them, can be overlapping, correlated, and/or causally associated. This figure summarises this context, with lines between sections indicating an association between the connected factors. This figure summarizes evidence from the following sources: (Abdel-Shafy & Mansour, 2016; Barceloux & Barceloux, 1999; Bhargava & Mariam, 1991; Davies-Colley & Smith, 2001; Freeman et al., 2004; Keeney & Hatfield, 2008; Kirk, 1985; Kroupova, Machova, & Svobodova, 2005; Lin, Zhu, Zhang, & Lin, 2019; Loiselle et al., 2008; Madrid & Zayas, 2007; Manoli & Samara, 1999; Mullins, 2009; Oke, 1966; E. Oliveira-Filho et al., 2014; Takada et al., 1978; Van Dam et al., 2010; H. Wang & Zhang, 2019; L. Wang et al., 2017; Water Research Australia, 2013; Xia et al., 2004; Xiao, Räike, Hartikainen, & Vähätalo, 2015).

Method

The search string (following the PICO method), timing and databases, and selection process is outlined in figure 2. Following the historical distinction between controlled and uncontrolled fires (Bixby et al., 2015), this review focuses on uncontrolled fires due to their tendency to be more widespread, intense, and related to other relevant environmental factors (such as prolonged drought). Fuel is noted according to a synthesis of prior schemes (chiefly (Andrews, 1986; Europe, 2011)): grassland, shrubland, eucalypt, other evergreen, deciduous, or mixed. It is important to note that eucalyptus forests produce ash that is chemically distinct from that found in other forest types (Harper et al., 2019). Exploration of the mobilisation or fates of ash leachates in laboratory settings are covered extensively elsewhere (e.g. Balfour, Doerr, & Robichaud, 2014; E. C. Oliveira-Filho et al., 2018), so are beyond the scope of this review

This review notes the time between fire events and measures, and where possible comments on longitudinal findings. This is due to the expectation that immediate factors influencing water quality (such as acute variation in water temperature (Hitt, 2003)) – can attenuate quickly, while others (such as longer-term increase in water temperature due to loss of vegetation that provided shade over water (Mahlum, Eby, Young, Clancy, & Jakober, 2011)) may only become apparent in following months and years (Minshall, Robinson, & Lawrence, 1997; Moody, Shakesby, Robichaud, Cannon, & Martin, 2013). Further detail on the literature and logic underlying these choices can be found in the supplementary materials.

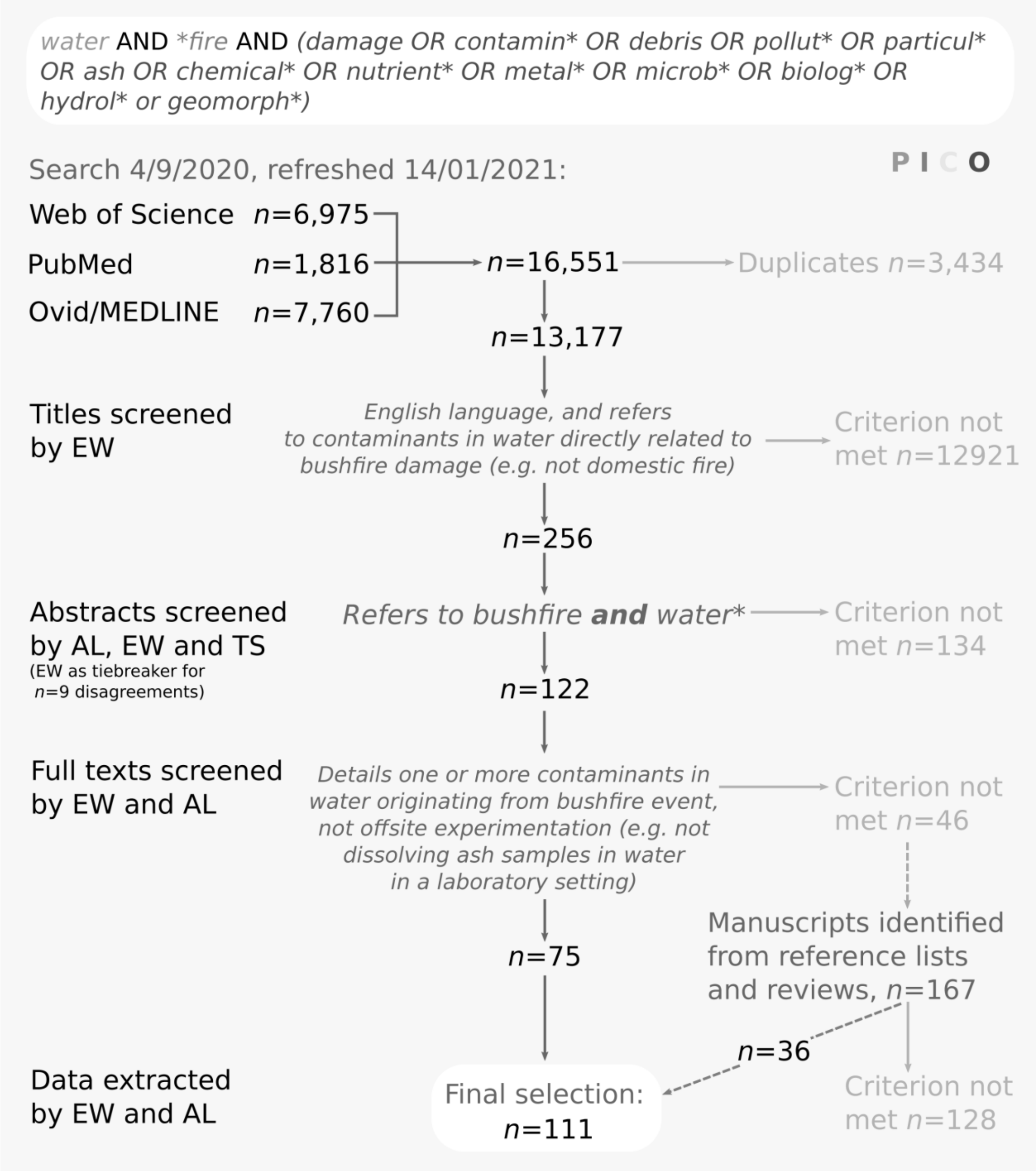
Findings are presented under the following major groupings:

1 Physical: suspended solids (woody debris, suspended sediment, particle size, other solids), turbidity and light attenuation, colour, Acidity/alkalinity (pH), conductivity, temperature, water course (transport, morphology, denudation).

2 Chemical: nutrients (nitrogen, ammonia and ammonium, nitrite and nitrate, phosphorous and phosphate, dissolved organic carbon), metals (calcium, magnesium, manganese, iron, copper, zinc, hardness, strontium, nickel, and others), salts (total ions, chloride, sodium, sulfate, potassium, and others), polycylic aromatic hydrocarbons (PAH) , toxic heavy metals (mercury, lead, cadmium), and others.

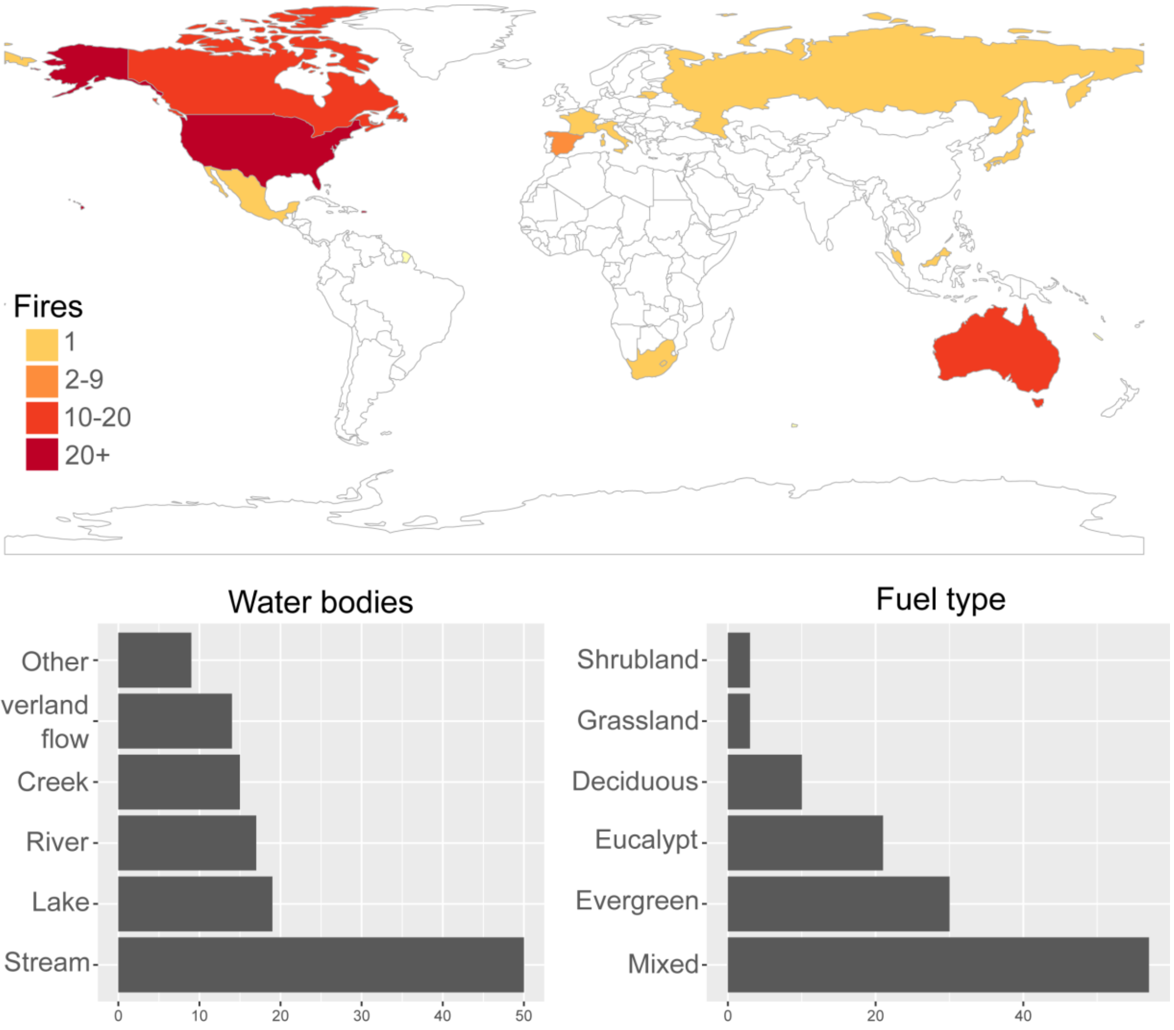
3 Biological: biomass (both directly measured and inferred from indicators), living organisms (small and large), and species diversity.

Figure 2. Overview of search and study selection.



Note: As of August 2020 (4/9/2020), search and abstract screening criterion was originally that manuscripts must refer to bushfire *and* water *and* an Australian context, but from 3,949 unique results (prior to duplicate removal, Web of Science *n*=230, PubMed *n*=118, OVID/MEDLINE *n*=3,971) only *n*=7 manuscripts met these criteria. The requirement for Australian context was removed and the search refreshed 14/1/2021. All results from the original search were included in this refreshed search. The screening process and subsequent review reports results from this refreshed search.

Figure 3. Geographical distribution of fires, and summary of water bodies and fuel types, in included manuscripts

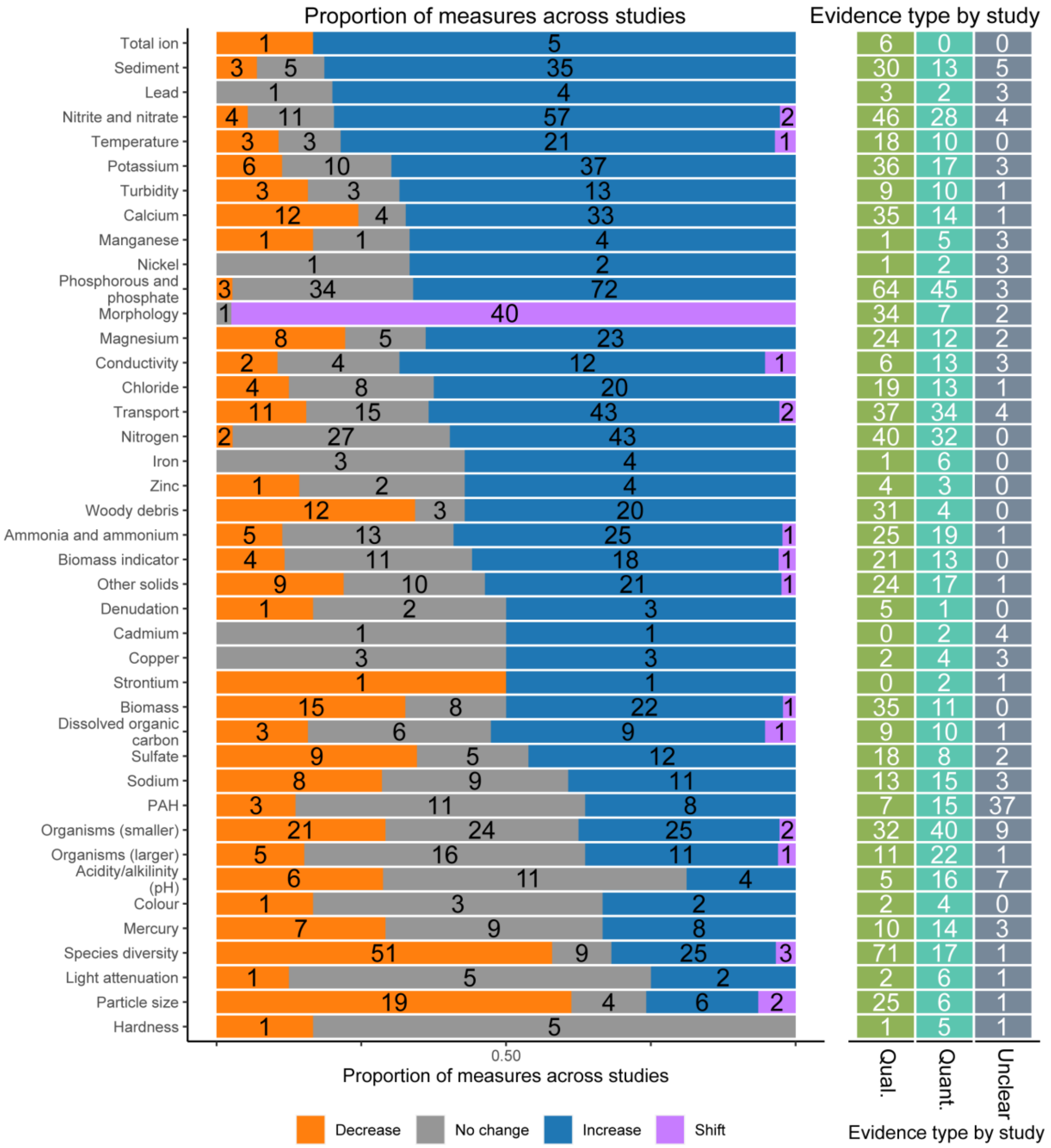


Note. Numbers are larger than total number of included manuscripts in the systematic search, as some manuscripts reported results for multiple fire events. Map generated in R with the *choroplethr* package v3.7.0.

Results

The systematic review revealed 111 manuscripts. These manuscripts concerned 139 fire events across 13 countries, with some overlap for major fire events (e.g. the extensive wildfires in 1988 in Yellowstone, United States of America). The majority of manuscripts (*n*=73) concerned fires in the United States of America, followed by Australia (*n*=19), Canada (*n*=13), and the remainder in France, Italy, Malaysia, Spain, Japan, Mexico, Portugal, Russia, and South Africa. The most common water body focused on was the stream. Eucalyptus was the primary fuel type in 21 manuscripts, with the most common fuel type being ‘mixed’. Figure 4 summarises evidence in this review. For clarity, results in subsequent sections will refer to manuscripts identified as relevant in the review by numbers which correspond to their designation in the supplementary tables. We report both the number of measures and the number of manuscripts from which these measures were extracted. Percentages are derived from manuscripts reporting precise numbers of either pre- vs post-fire or burned vs unburned reference water body, and are expressed as the increase or decrease relative to the pre-fire or unburned control measures. Interpretation of evidence in text is on the basis of balance of evidence: that is, if 50% or more of measures report findings in the same direction (increase, decrease, no change), this direction is discussed. “Mixed” results refer to circumstances where there is equal evidence for different effects. “Unclear” results may arise from measurement failures (e.g. amount below detection limits, equipment failure), measures that original authors of manuscripts interpret as unclear or unreliable in text, or cases where a measure was described in the methods section but results could not be found in the manuscript. For many of the factors discussed, multiple measurement approaches have been collapsed for the purpose of summary. Further detail and all underlying information are presented in supplementary materials.

Figure 4. Visual overview of all results.

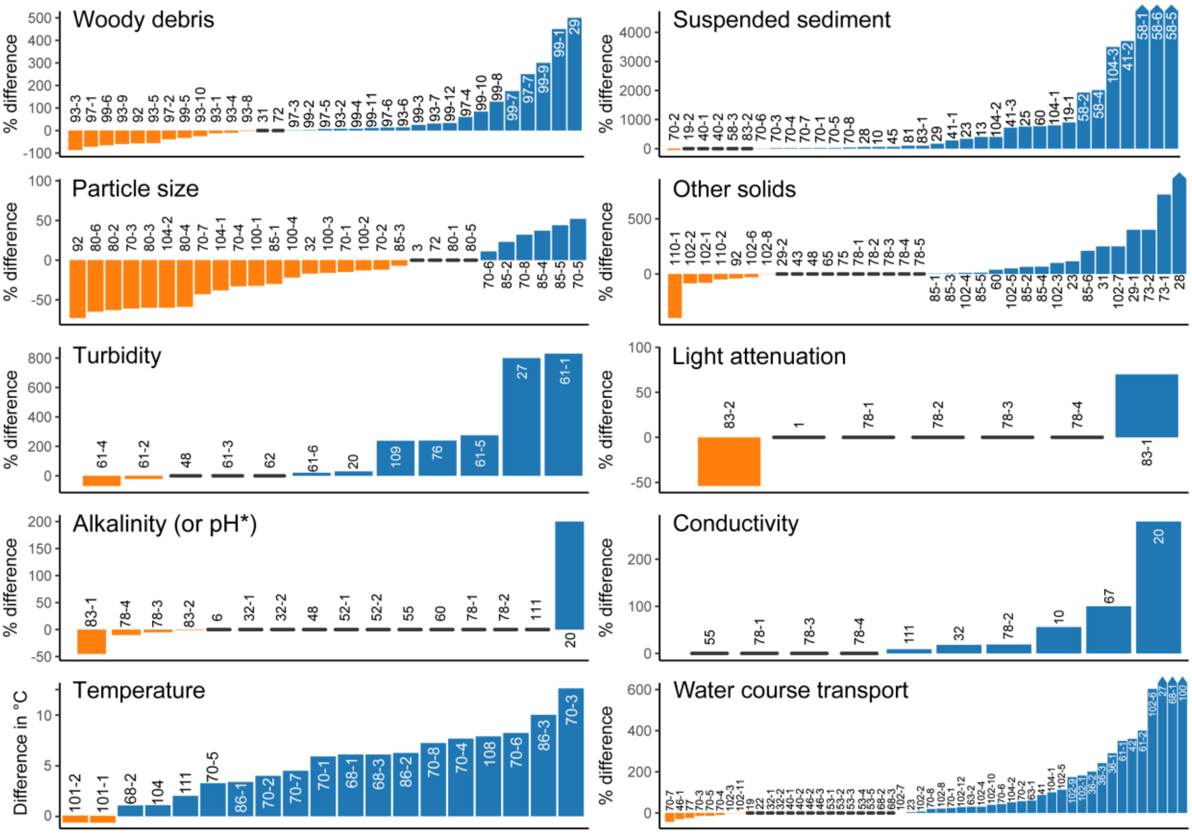


Note. “Increase” and “Decrease” is a composite of measures relative to pre-fire measures in the same water body, and relative to matched controls. “Shift” indicates some change that cannot be quantified in terms of increase or decrease of a specific number, such as changes in macroinvertebrate community structure, or alterations to streambed profile. This portion of the figure omits inconclusive or unclear results, which are enumerated instead in the “evidence type by study”. Where longitudinal or repeated measures were reported, this figure includes only the first measures after the fire. Longitudinal evidence is discussed separately. Further detail on these points can be found in subsequent figures, and supplementary tables.

Physical

Figure 5 provides an overview of evidence for physical factors where percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated.

Figure 5. Summary of percentage change reported for physical characteristics.



Note. This figure summarises evidence where precise numbers were reported and percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated. Numbers within the plot correspond to publications enumerated in supplementary materials. A dash followed by a number indicates multiple measures (typically referring to different water bodies) reported from the same paper are included. Arrows at the top of bars indicate values continue, but axes were truncated so that less extreme values could be legible. Water course morphology is omitted due to the differing measures (e.g. channel width is not comparable with change in total area, or scouring). * to account for different constituent measures an “increase” in this figure consistently refers to more alkaline and “decrease” refers to more acidic.

Suspended solids

Suspended solids are particles that are not dissolved in water. Woody debris consists of fragments that were not leaf litter (e.g. broken roots, bark). The balance of evidence suggests that bushfire may increase the presence of woody debris by an average of 110%, for at least two years following the fire. Of the eight papers that focused on woody debris, we extracted a total of 35 measures (see 15, 29, 31, 72, 92, 93, 97, 99). Over 50% took measurements up to 2 years post fire, followed by measurements less than one year post fire (38%) and one year post fire (9%). Of the measures extracted, 34% recorded a decrease in suspended solids following fire, 57% recorded an increase, 6% recorded no change following fire, and 3% had unclear results. Manuscripts also included some commentary on the impact of bushfire on debris orientation relative to shore (93, 97), with one manuscript (93) suggesting that bushfire is associated with increased duration of debris presence in water.

Suspended sediment was characterised in terms of load, discharge, or concentration in the majority of manuscripts included. Suspended sediment was substantially increased (by an average of over 1000%) following bushfire. The majority of evidence was collected less than a year after a fire. Of the 27 papers that focused on sediment (4, 5, 8, 10-13, 15, 18-20, 23, 25, 28, 29, 40, 41, 45, 58, 60, 62, 64- 66, 70, 81, 83, 104), that used a total of 50 measures, 65% took measurement less than a year after fire, 35% one year post fire and 3% reported measures 10 years post fire. Of the measures used, 6% recorded a decrease in suspended sediment following fire, 73% recorded an increase, 10% of the measures reported no change following fire, and 10% were unclear.

Other manuscripts reported on suspended solids such as leaf litter input, accumulation, or loss over time (31, 92, 110) with mixed directions of findings. Limited discussion of organic matter yield or export was suggestive of an increase associated with bushfire (60, 75, 85). Evidence regarding total dissolved solids (48, 64, 65, 78), total suspended solids (23, 39, 73, 64,65,102), and total volatile solids i.e. loss of solid mass on ignition (102), was mixed.

Overall, bushfire was associated with smaller suspended particle size. Of the 12 papers that focused on particle size, that used a total of 33 measures, 52% took measurement one year after fire, 30% reported measures five years after the fire, and 17% reported measures less than one year post fire. Of the measures used, 59% recorded a decrease in suspended particle size following fire, 19% recorded an increase, 12% reported no change, and 6% recorded a shift (without specifying direction).

Turbidity

On balance, evidence suggests bushfire increases turbidity by an average of 348% within one year of a fire. Of the 13 papers that focused on turbidity (11, 17, 20, 27, 48, 60-62, 76, 84, 105, 107, 109), we found a total of 20 measures. Approximately half (53%) took measurement less than one year after fire, and 47% reported measures one year after the fire. Of the measures extracted, 15% recorded a decrease in turbidity following fire, 65% recorded an increase, 15% reported no change, and for 5% the direction of change was unclear.

Light attenuation and water colour

Bushfires did not consistently impact light attenuation or colour, and approximately half of papers found no effect. Of the 13 papers that focused on light attenuation (1, 2, 31, 78, 83), that used a total of nine measures, all studies took measures within a year following the fires. Of the measures extracted, 11% recorded a decrease following fire, 22% recorded an increase, 56% reported no change, and for 11% the direction was unclear. Of the six papers that focused on water colour (30, 48, 52, 60, 71, 83), that used a total of six measures, studies were equally distributed across the time since fire (1 year, less than one year and three years post fire). Of the measures used, 17% recorded a decrease in colour concentration following fire, 33% recorded an increase, and 50% reported no change.

Alkalinity and pH

The evidence regarding the impact of bushfire on pH was heterogenous. There were a number of different operationalisations of alkalinity (e.g. on the pH scale, or as total acid neutralisation capacity). Of the 19 papers that focused on pH (6, 10, 11, 13- 15, 17, 20, 32, 48, 52, 55, 60, 64, 65, 78, 83, 105, 111), that used a total of 29 measures of acidity, alkalinity, or pH, 55% took measurements less than one year after fire, 37% reported measures one year after the fire, and 9% reported measured three years post fire. Of the measures used, 21% recorded a decrease in alkalinity (or increase in pH) following fire, 14% recorded an increase, 39% reported no change, and in 25% the direction was unclear. This is highly likely to be due to the context-specific complex, time-varying and interactive factors underlying water pH (for an introduction to this complex topic, see chapter 10 of (VanLoon & Duffy, 2006)).

Conductivity

On balance, bushfires increased the conductivity of water bodies by an average of 80% within one year of the fire event. Nineteen manuscripts included 23 measures of conductivity (10, 13, 14, 15, 17, 20, 27, 32, 44, 55, 60, 62, 64, 65, 67, 68, 78, 84, 111), which were taken within the same year (70%) or one year (30%) of the fire. Nine percent reported a decrease in conductivity, 55% an increase, 18% found no change, one manuscript (5%) reported a decrease immediately followed by increase (recorded as a “shift” in figure 3), and 14% had unclear results.

Temperature

Findings clearly demonstrate that bushfires can increase water temperature within the year following a fire. Of the 14 papers that focused on temperature (10, 17, 31, 55, 60, 62, 68, 70, 72, 86, 101, 104, 108, 111), that used a total of 29 measures, 71% took measurement less than one year after fire, and 29% reported measures one year after the fire. Of the measures used, 11% recorded a decrease in temperature following fire, 75% recorded an increase, 11% reported no change, and 4% record a shift of greater seasonal variation in temperature. All reported temperatures were above zero, and as reported in figure 4, the impact of bushfire on water temperature corresponded to increases between 1 and 12.5 degrees centigrade.

Water course

Transport

With regard to transport (considered here as an aggregate of velocity, baseflow, surge flow and runoff), there is evidence that bushfire is associated with increased transport by an average of 417% at least one year after the fire. Of the 31 papers that focused on transport (5, 19, 22, 23, 27, 32, 36, 37, 39, 40, 41, 42, 46, 47, 53, 54, 58, 60-63, 65, 66, 68, 70, 74, 76, 77, 100, 102, 104), using a total of 76 measures, 23% took measurements less than one year after fire, 71% reported measures one year after the fire, and 1% and 5% reported measures two and five years post fire respectively. Of the measures used, 15% recorded a decrease following fire, 57% recorded an increase, 20% reported no change, and in 5% the direction was unclear.

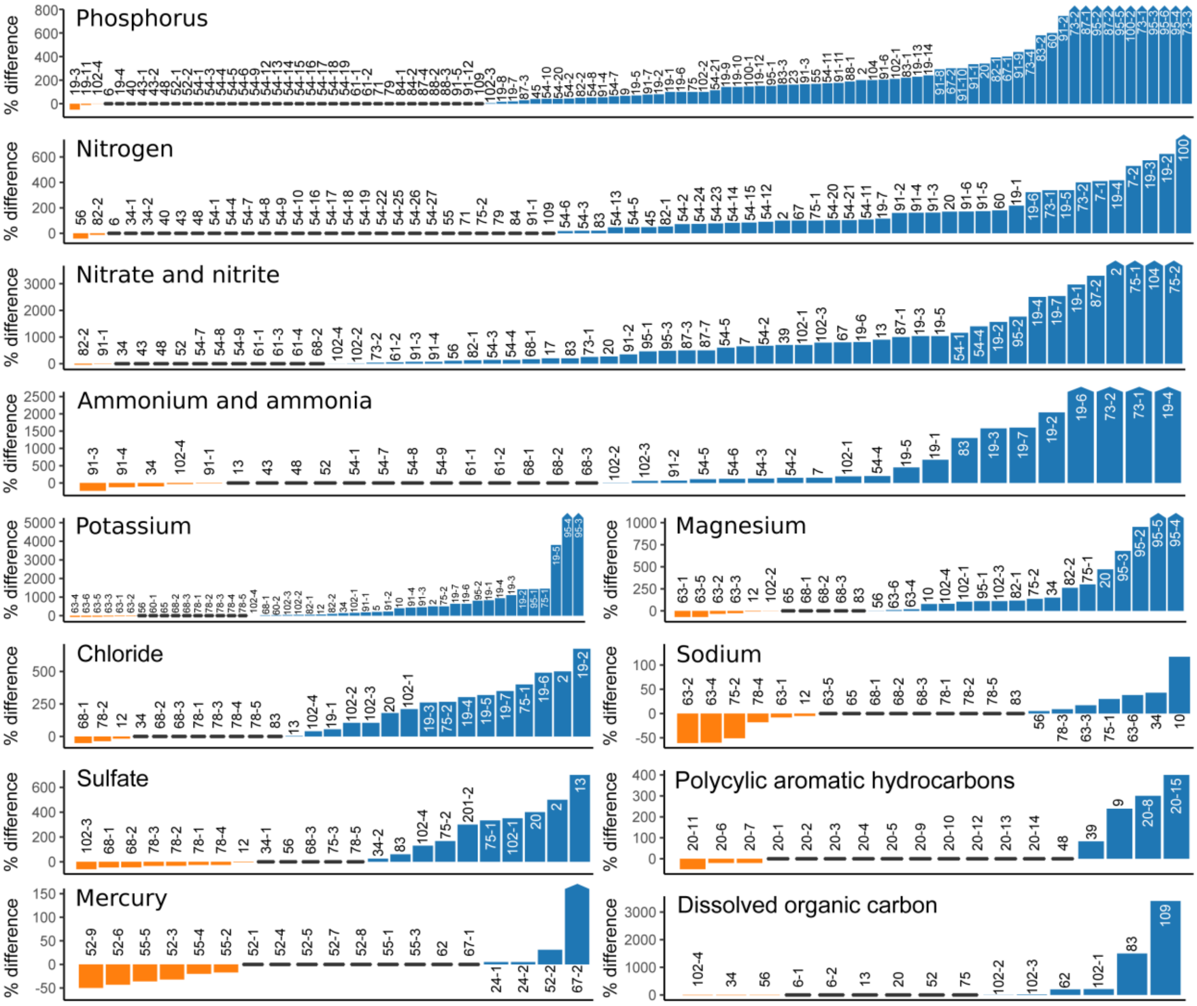
Morphology

There was evidence that bushfires impacted water body morphology, generally being associated with wider and shallower channels and riffles (riffles are areas of shallow water caused by deposition of sediment). Papers describing morphology changes during fire included alterations to water channel width, riffle width and depth, width: depth ratio, and scouring. Of the 13 papers that focused on morphology (15, 25, 29, 32, 46, 51, 62, 70, 89, 90, 97, 100, 104), with 44 measures, 38% took measurement less than one year after fire, 50% reported measures one year after the fire, and the remaining measures were taken between two and five years post fire. Synthesis across all morphological characteristics is not possible, but alongside observations of the association of bushfire with wider and shallower channels (90), and mixed findings regarding scouring (increase reported in manuscript 29, but not in 32), water body width (reported in manuscripts 70, 104) increased in eight of ten measures by an average of 207%, and the width to depth ratio (reported in 70) increased in seven of eight measures by an average of 158%.

Chemical

Figure 6 provides an overview of evidence for chemical factors where percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated.

Figure 6. Summary of percentage change reported for chemical characteristics.



Note. This figure summarises evidence where precise numbers were reported and percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated. Numbers within the plot correspond to publications enumerated in supplementary materials. A dash followed by a number indicates multiple measures (typically referring to different water bodies) reported from the same paper are included. Peaks indicate axis truncation for the purposes of legibility.

Nutrients

Nitrogen

Results indicated that bushfires were associated with a 258% increase in nitrogen on average in water in up to two years after a fire event. Of the 29 papers that measured nitrogen (2, 6, 7, 14, 19, 20, 30, 34, 40, 43, 45, 48, 54, 55, 56, 60, 64, 65, 67, 71, 73, 75, 79, 82-84, 91, 100, 109) using a total of 74 measures, 32% reported measurement less than one year after fire, 22% reported measures one year after the fire, and 46% reported measures two years post fire. Of the measures used, 3% recorded a decrease in nitrogen following fire, 60% recorded an increase, and 38% reported no change.

Ammonia and ammonium

While it was unclear whether ammonia and ammonium increased after a fire, those manuscripts reporting an increase found a very high average increase (>5000%), which we posit is due to the introduction of ammonia and ammonium to a system with previously negligible levels. For example the 24900% increase in ammonia concentration reported in manuscript 9 represents ammonia levels of 1 μg/L in unburned creeks, compared with 250 μg/L in burned creeks. Of the 21 papers that measured ammonia and ammonium (7, 9, 11, 13, 17, 19, 20, 28, 34, 43, 48, 52, 54, 61, 64, 65, 68, 73, 83, 91, 102) using a total of 46 measures, 55% took measurement less than one year after fire, 18% reported measures one year after the fire, 24% reported measures two years after the fire and 3% reported measures three years post fire. Of the measures used, 11% recorded a decrease in ammonium and/or ammonia following fire, 56% recorded an increase, 29% reported no change, 2% reported a shift but the direction was unspecified, and 2% were unclear.

Nitrite and nitrate

Findings indicated that fires were associated with an increase in nitrate and nitrite levels. Much like ammonia and ammonium, we infer the high average increase percentage (average increase where an increase was reported of 1550%) likely reflects very low levels in pre-fire or comparison water bodies, for example in (13) a 1566% increase in NO_3^- represents a change from 0.074 $mg \cdot L^{-1}$ pre-fire to 1.233 post-fire $mg \cdot L^{-1}$. Of the 35 papers that measured nitrite and nitrate (2, 7, 9, 11, 13, 15, 17, 19, 20, 28, 30, 31, 34, 39, 43, 48, 52, 54, 56, 61, 62, 64, 65, 67, 68, 73, 75, 82-84, 87, 91, 95, 102, 104) using a total of 79 measures, 46% took measurement less than one year after fire, 40% reported measures one year after the fire, 12% reported measures two years post fire, and 1.5% reported measures three years post fire. Of the measures used, 5% recorded a decrease in nitrite and/or nitrate following fire, 73% recorded an increase, 14% reported no change, and 3% reported a shift (an increase specifically related to storm events).

Phosphorus and phosphate

Bushfires increased the phosphorus and phosphate, with the average reported increase following a similar trend to the previously discussed nutrients. Of the 39 papers that measured phosphorus and phosphate (2, 6, 9, 11, 14, 17, 19, 20, 23, 35, 39, 40, 43, 45, 48, 50, 52, 54, 55, 60, 61, 64, 65, 67, 71, 73, 75, 79, 82-84, 87, 88, 91, 95, 100, 102, 104, 109) using a total of 113 measures, 48% took measurement less than one year after fire, 31% reported measures one year after the fire, 19% two years post fire, and 2% reported measures three years post fire. Of the measures used, 3% recorded a decrease in phosphorus and/or phosphate following fire, 64% recorded an increase, 30% reported no change, and 3% were unclear.

Dissolved organic carbon (DOC)

Results regarding the impact of bushfire on dissolve organic carbon were mixed. Of the 16 papers that directly measured DOC (2, 6, 13, 14, 20, 21, 30, 34, 52, 56, 62, 75, 83, 102, 106, 109) using a total of 21 measures, 27% took measurement less than one year after fire, 60% reported measures one year after the fire, and 7% reported measures three and 10 years post fire respectively. Of the measures used, 15% recorded a decrease in dissolved organic carbon following fire, 45% recorded an increase, 30% reported no change, and 5% reported a shift but the direction was unclear.

Metals

Calcium

On balance, bushfires increased the amount of calcium in of water bodies, with most measures taking place within one year of the fire. Amongst those papers finding an increase, the average percentage increase was 1335%. Of the 22 papers that reported on calcium (2, 5, 10, 11, 12, 13, 14, 17, 19, 20, 34, 56, 63, 64, 65, 68, 75, 78, 82, 83, 95, 102) using a total of 55 measures, 41% took measurement less than one year after fire, and 59% reported measures one year after the fire. Of the measures used, 24% recorded a decrease in calcium following fire, 66% recorded an increase, 8% reported no change, and 2% were unclear.

Magnesium

On balance, bushfires were associated with an increase in the amount of magnesium in water, with an average increase of 2638% amongst those papers reporting an increase. Of the 19 papers that measured magnesium (5, 10, 11, 12, 13, 14, 17, 20, 34, 56, 63, 64, 65, 68, 75, 82, 83, 95, 102) using a total of 40 measures, 39% took measurement less than one year after fire, and 61% reported measures one year after the fire. Of the measures used, 21% recorded a decrease in magnesium following fire, 61% recorded an increase, 13% reported no change, and 5% were unclear.

Manganese

It was not clear whether bushfires were associated with manganese. Of the 7 papers that measured manganese (10, 20, 40, 62, 64, 65, 103) using a total of 11 measures, 85% took measurement less than one year after fire, and 15% reported measures one year after the fire. Of the measures used, 11% recorded a decrease in manganese following fire, 44% recorded an increase, 11% reported no change, and 33% were unclear.

Iron

There was relatively little evidence relating to the impact of bushfire on iron in water. Of the six papers (10, 20, 40, 48, 62, 64) that measured iron using a total of seven measures, 75% took measurements less than one year after fire and 25% one year after the fire. Of the measures used, 57% recorded an increase in iron, and 43% reported no change.

Copper

Of the six papers that measured copper (20, 33, 39, 48, 64, 103) using a total of nine measures, 87% took measurements less than one year after fire, and 13% measures one year after the fire. Of the measures extracted, results were equivocal with 33% reporting an increase, no change and unclear results respectively.

Zinc

Of the six papers that measured zinc (10, 20, 33, 39, 48, 64) using a total of seven measures, 83% took measurement less than one year after fire, and 17% reported measures one year after the fire. Of the measures used, 57% recorded an increase in zinc, 14% recorded a decrease, and 43% reported no change.

Hardness

"Hardness" typically describes water with high alkaline earth metal content (primarily magnesium and calcium, and other multivalent cations such as iron, aluminium, and zinc (E. Oliveira-Filho et al., 2014; Sengupta, 2013)).Of the three papers that measured hardness (15, 32, 78) using a total of seven measures, all studies reported measures one year after the fire. Of the measures used, 71% recorded no change in hardness, 14% recorded a decrease, and 14% were unclear.

Salts

Total ions

Bushfires were associated with an increase in concentration in water within one year of the fire event, with an average reported increase (amongst those measures reporting an increase) of 161%. Of the three papers (75, 83, 95) that measured total ions using a total of six measures, all studies reported measures one year after the fire. Of the measures used, 83% reported an increase in total ions, and 17% recorded a decrease.

Chloride

On balance, evidence suggested that bushfires were associated with an increase in chloride, with an average reported increase of 266% within one year of the fire. Of the 16 papers that measured chloride (2, 5, 11, 12, 13, 17, 19, 20, 34, 64, 65, 68, 75, 78, 83, 102) using a total of 34 measures, 53% reported measures less than one year after the fire and 47% reported measures one year after the fire. Of the measures used, 61% recorded an increase in chloride, 12% recorded a decrease, 24% reported no change, and 3% were unclear.

Sodium

Evidence surrounding the impact of bushfires on sodium levels was mixed. Of the 17 papers that measured sodium (5, 10, 11, 12, 13, 14, 17, 20, 34, 56, 63, 64, 65, 68, 75, 78, 83) using a total of 32 measures, 39% reported measures less than one year after the fire and 61% reported measures one year after the fire. Of the measures used, 35% recorded an increase in sodium, 26% recorded a decrease, 29% reported no change, and 10% were unclear.

Sulfate

Evidence for the association between sulfate concentration and bushfire was mixed. Of the 16 papers that measured sulfate (2, 5, 11, 12, 13, 17, 20, 34, 56, 64, 65, 68, 75, 78, 83, 102) using a total of 30 measures, 37% reported measures less than one year after the fire and 63% reported measures one year after the fire. Of the measures used, 43% recorded an increase in sulfate, 32% recorded a decrease, 18% reported no change, and 7% were unclear.

Potassium

On balance, evidence suggested that bushfires were associated with an increase in potassium. We interpret the large magnitude of the average reported increase (8508%) arising from levels tending to be very low prior to fire or in comparison water bodies. Of the 24 papers that measured potassium using a total of 58 measures, 44% reported measures less than one year after the fire and 56% reported measures one year after the fire. Of the measures used, 66% recorded an increase in potassium, 11% recorded a decrease, 18% reported no change, and 5% were unclear.

Polycyclic aromatic hydrocarbons (PAH)

The majority of results surrounding the relationship between bushfires and PAH levels were unclear. Of the eight papers (9, 16, 20, 30, 39, 48, 65, 103) that measured PAHs using a total of 59 measures, all studies reported on measures less than one year after the fire. Of the measures used, 14% recorded an increase in PAH, 5% recorded a decrease, 19% reported no change, and (63%) were unclear.

Toxic heavy metals

Mercury

Evidence surrounding the impact of bushfires on mercury in water was mixed. Of the six papers (24, 52, 55, 62, 64, 67) that measured mercury using a total of 27 measures, 33% reported measures less than one year after the fire and 67% reported measures three years after the fire. Of the measures used, 30% recorded an increase in mercury, 26% recorded a decrease, 33% reported no change, and 11% were unclear.

Lead

It was largely unclear whether bushfires were associated with lead in water, with the balance of evidence supporting some increase. Of the six papers (20, 33, 39, 48, 64, 103) that measured lead using a total of eight measures, majority (87%) reported measures less than one year after the fire and 14% reported measures one year after the fire. Of the measures used, 50% recorded an increase in lead, 12% reported no change, and 38% were unclear.

Cadmium

Evidence for the impact of bushfire on cadmium in water was largely unclear. All of the four papers (20, 48, 64, 103) that measured cadmium using a total of six measures reported measures less than one year after the fire. Of the measures used, 17% recorded an increase in cadmium, 17% reported no change, and majority (67%) were unclear.

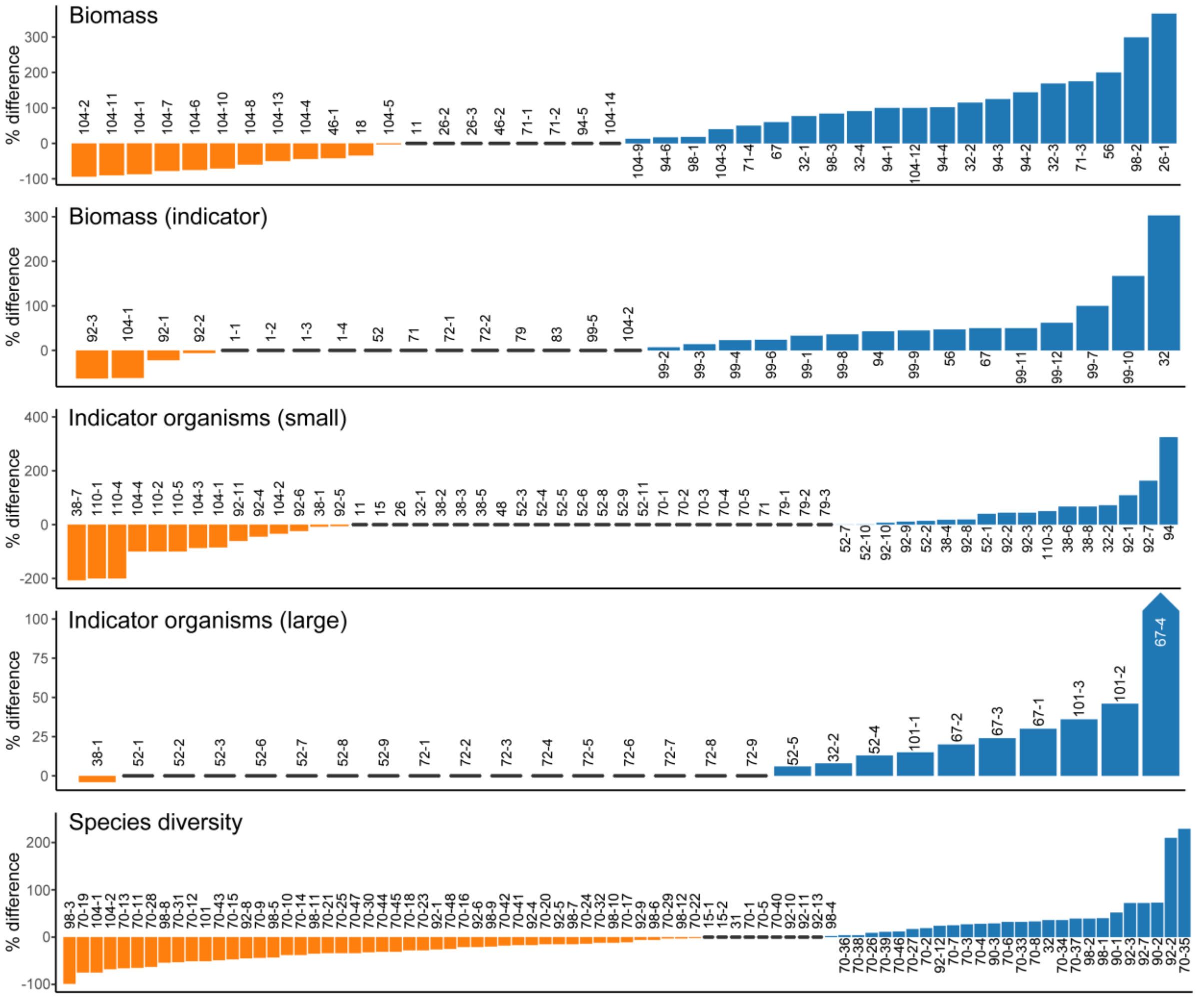
Others

Some measures were also extracted for metals (including for strontium, nickel, cobalt, silver, aluminium, chromium, tin, vanadium, barium, beryllium, and titanium), salts (including flouride), metalloids (antimony and arsenic), and heavy metals or other contaminants (such as *p*-cresol) but there was insufficient information to synthesise findings. The interested reader is encouraged to consult the supplementary materials.

Biological

Figure 7 provides an overview of evidence for chemical factors where percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated.

Figure 7. Summary of percentage change reported for biological characteristics.



Note. This figure summarises evidence where precise numbers were reported and percentage difference (either between pre- and post- fire measures, or between control water body and fire-affected body) could be calculated. Numbers within the plot correspond to publications enumerated in Supplementary Materials. A dash followed by a number indicates multiple measures (typically referring to different water bodies) reported from the same paper are included. Peaks indicate axis truncation for the purposes of legibility.

Biomass

Fifteen manuscripts discussed the impact of fire on biomass measured in terms of mass or density (3, 11, 14, 15, 18, 26, 32, 46, 49, 56, 67, 71, 94, 98, and 104). Most (98%) of the 43 reported measures were taken a year or less after the fire event. Evidence was equivocal, with 49% indicating an increase in biomass, 35% a decrease, 2% some other effect or shift, and 14% showing no effect. Fourteen manuscripts inferred biomass indirectly (1, 14, 15, 32, 52, 56, 67, 72, 79, 83, 92, 94, 99, 104), largely via chlorophyll a, retinoic acid, and hormonal activity (e.g. estrogenic activity reported in (2)). Most measures were taken at less than one year (53%) or one year (43%) after the fire. Measured this way, evidence was supportive of either an increase

(56% of measures) or no change (31% of measures) in biomass.

Indicator species

Small

Macroinvertebrates were the most commonly used measured indicator species, followed by diatoms. Of the 20 papers that measured biomass using small indicator species and a total of 81 measures, 29% took measurement less than one year after fire, 49% reported measures one year after the fire, and 22% reported measures three years post fire. Of the measures used, 26% recorded a decrease following fire, 31% recorded an increase in abundance or biomass, 30% reported no change, and 2% reported a shift and 11% were unclear.

Large

Trout was the most commonly reported large indicator species. Of the eight papers that indirectly measured biomass using large indicator species and a total of 36 measures, 47% took measurement less than one year after fire, and 53% reported measures three years post fire. Of the measures used, 15% recorded a decrease in density or body size following fire, 32% recorded an increase, 47% reported no change, and 3% reported a shift and 3% were unclear.

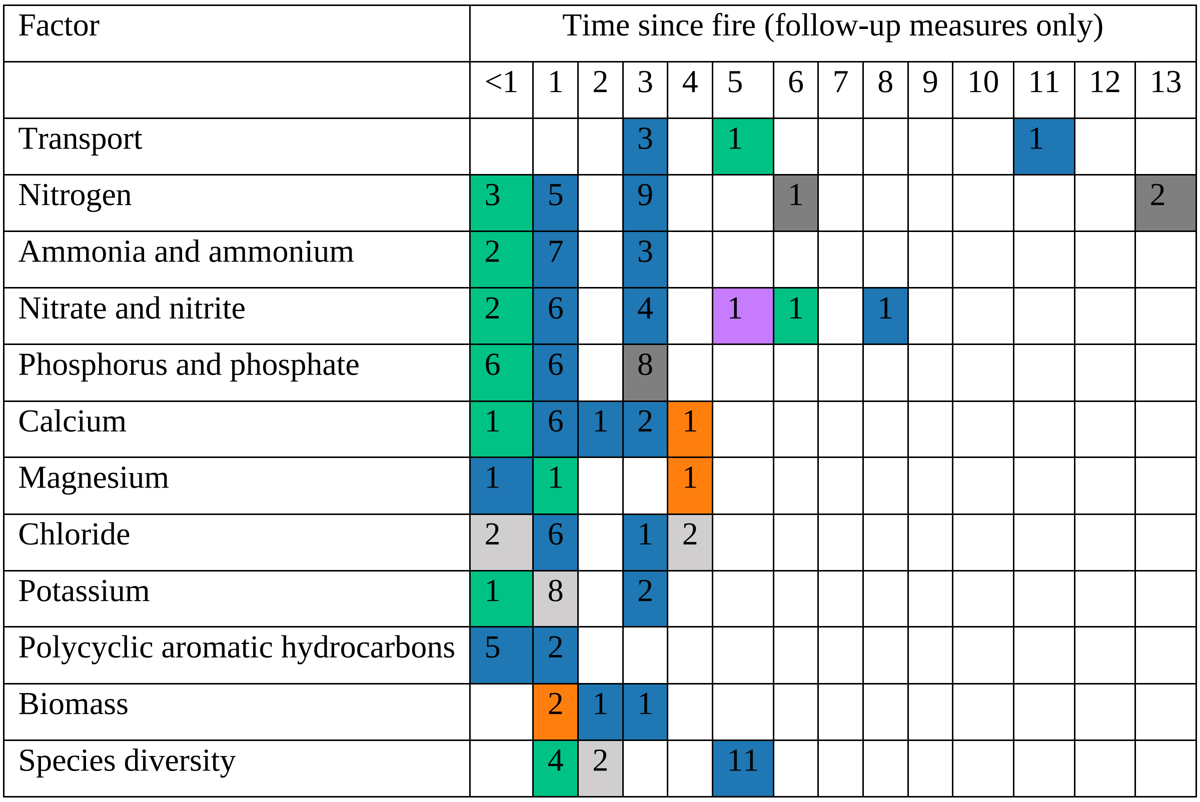
Species diversity

On balance, evidence suggested that bushfires decreased species diversity. The 14 manuscripts reporting on species diversity (14, 15, 26, 31, 32, 49, 50, 70, 90, 92, 98, 101, 104, 110) reported a remarkable 92 measures, due to applying multiple measures of diversity and focussing on multiple subcategories of species. Measures included relative abundance or taxa composition (in 15, 31, 49, 92, 98), Shannon’s diversity index (in 70, 90), Simpson’s index (in 70), taxonomic richness (in 15, 98), species richness (in 32, 70), Chao taxa estimator (in 98), and variation of specific groups per the Jaccard index (in 92). Over half (55%) of measures were taken within less than a year of the fire, while 45% were taken the year after the fire. Taken together, those manuscripts reporting a decrease in species diversity indicated an average 34% decrease in diversity following bushfire.

Longitudinal impacts of fire

A subset of the identified manuscripts included repeated samples over time. The follow-up period was typically within three years of the fire event, though some studies did report longer follow-up periods. Table 1 summarises results from the final measure in longitudinal studies (relative to first measures) for those factors with multiple longitudinal measures. Overall there is some indication that if factors do not return to baseline (or equality with control water bodies) within a year of the fire event, they are likely to remain elevated, decreased, or shifted in some manner congruent with the original impact of the fire. The interested reader is encouraged to consult the supplementary materials for further detail.

Table 1. Summary of available longitudinal data



Factor	Time since fire (follow-up measures only)													
	<1	1	2	3	4	5	6	7	8	9	10	11	12	13
Transport				3		1						1		
Nitrogen	3	5		9			1							2
Ammonia and ammonium	2	7		3										
Nitrate and nitrite	2	6		4		1	1		1					
Phosphorus and phosphate	6	6		8										
Calcium	1	6	1	2	1									
Magnesium	1	1			1									
Chloride	2	6		1	2									
Potassium	1	8		2										
Polycyclic aromatic hydrocarbons	5	2												
Biomass		2	1	1										
Species diversity		4	2			11								

Note. Numbers indicate the number of measures reporting that particular impact. They reflect the dominant status only (50% or more measures concurring for that particular time point), see supplementary materials for proportional breakdown for each factor. Colour meaning is as follows: [no change from baseline/comparison] [still increased] [still decreased] [still shifted] [returned to baseline/comparison] [evidence evenly split]

Fuel type

A subset of the identified factors had sufficient data to explore the association between fuel type (grassland / shrubland / eucalypt / other evergreen / deciduous / mixed) and impact of bushfire. Contingent on sample and cell size, either no analysis, Fisher's exact test or Chi Squared values were calculated (see supplementary materials for further details, and all results). These tests reached α<0.05 for other solids, acidity/alkalinity, water course transport, water course morphology, nitrogen, phosphorous and phosphate, calcium, potassium, PAH, mercury, biomass, smaller indicator organisms, and species diversity. However, due to the predominance of “mixed” fuel type, *post-hoc* comparisons were not tenable thus further investigation of the potential role of fuel on bushfire impact was not possible.

Discussion

This review has established a thorough overview of the current state of peer-reviewed evidence surrounding changes occurring in surface freshwater systems following bushfires. This information is an important element of drinking water management (Nunes et al., 2018), which has historically been a driving concern for research on the impacts of bushfire on water (Lane et al., 2010; Pachauri et al., 2014). A corollary of this focus has been the development of a body of evidence to support conservation efforts, as environmental health and human drinking water management are inherently intertwined (Postel, 2007). Accordingly, this discussion will synthesise mechanistic inference to suggest underlying processes commonly discussed in human drinking water management, and an interactive perspective similar to that taken by Bixby et al. (2015) to reflect the interactive complexity of water ecosystems.

The published literature supports an increase in the total amount of suspended solids in water following fires. Suspended solids originate from soil erosion, re-suspension of sediments from the bottom of bodies of water (Kirk, 1985), or weathering of rocks (Bhargava & Mariam, 1991). It is likely that post-fire erosion is a key process in introducing solids into the water, given that large bushfires can increase sediment erosion and runoff in the existing soil to an extent comparable to anthropogenic land clearing and logging (Cannon, Bigio, & Mine, 2001; Richardson, Hatten, & Wheatcroft, 2018; Robichaud, Elliot, Pierson, Hall, & Moffet, 2009). We found evidence that bushfire was associated with increased transport (in terms of flow velocity and likelihood of surges following rain) that persisted longitudinally (with one reported measure at eleven years), increasing the likelihood of sediment re-suspension. Accelerated rock weathering may also contribute, given that we also found evidence for an increase in essential nutrients that enter water through erosion of rocks containing minerals like calcite and olivine (calcium, magnesium, and manganese, per (Aikawa, 1980; Cameron, 1990; Mousavi, Shahsavari, & Rezaei, 2011; Schot & Wassen, 1993; Water Research Australia, 2013; P. J. White & Broadley, 2003))[3]. Our findings that bushfire can impact water course morphology. We found fire is associated with wider and shallower channels, which comports

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[3] Note that we did not collect data on the specific geology of the burned areas, and this inference was not made within specific manuscripts.

with evidence that sediment and fire-related erosional processes change the geomorphology of waterways themselves on a long-term basis, from decades to centuries (Holloway et al., 2020; Jung, Hogue, Rademacher, & Meixner, 2009; Shakesby & Doerr, 2006).

Relatedly, we found strong evidence that bushfire was associated with a decrease in the size of suspended particulates. Particle size is an important factor impacting water quality (Bhargava & Mariam, 1991). Smaller particles (<2μm) such as clay, silicate materials (e.g. sand), and iron oxides and aluminium oxides remain suspended in water and contribute to turbidity by forming potentially indefinitely stable colloidal suspensions, while larger particles such as sand, gravel, and silt fall to the floor of the water body (Davies-Colley & Smith, 2001; Kirk, 1985).

Turbidity (the scattering of light by suspended particles) is connected to total suspended solid concentration, which includes inorganic particles and can change over time in accordance with water flow (Brown, 1984). Conversely, light absorption is associated with chromatophoric dissolved organic matter, algal, and phytoplankton concentrations (Bhargava & Mariam, 1991; Loiselle et al., 2008). Together, these factors inform the total light attenuation of a water body (Davies-Colley & Smith, 2001). Given we found evidence of an increase in total suspended solids and decrease in particle size (potentially supporting persistent colloidal suspensions), it is unsurprising that we found strong evidence that bushfires were associated with an increase in water turbidity (Kirk, 1985). However, we did not find clear evidence of bushfire impacting the absorptive aspect of total light attenuation (Davies-Colley & Smith, 2001). Events such as algal blooms can develop within days and dissipate within months (Heisler et al., 2008), which is likely to be missed in the current review, given measures tended to be taken at a later time (only two measures of light attenuation were taken less than a year after the fire event).

Turbidity can adversely affect plants by blocking photosynthetically-active wavelengths of light (400 to 700 nanometres) (Loiselle et al., 2008), impact animals by limiting how far they can see underwater and reduce the aesthetic quality of water for recreation (Davies-Colley & Smith, 2001). Conversely, high levels of suspended solids can serve as substrates for bacterial growth in situations of nitrification (Xia et al., 2004). These countervailing processes may be why evidence on the impact of fire on biomass was mixed, but somewhat supported no change. Biomass refers to the material produced by microorganisms, plants or animals (McNaught, Wilkinson, & Chalk, 2019), and we took care to separate direct measures (e.g. “microbial biomass” in (Palese, Giovannini, Lucchesi, Dumontet, & Perucci, 2004)), and biomass inferred from indicators such as environmental DNA in the water (e.g. (Takahara, Minamoto, Yamanaka, Doi, & Kawabata, 2012)).

Species diversity is calculated from the composition of component species in an environment (Resh & Unzicker, 1975). The balance of evidence indicated that fire negatively impacted species diversity, but in some instances was associated with an increase that persisted up to five years. The shorter-term decrease may be due to acute impacts of high temperature and other acute changes to the ecosystem (e.g. heat death in minnows has been noted after one day of exposure to high temperatures (Mundahl, 1990)). This long term increase may be due to fire adding variety in flowing water morphology (e.g. seeps, riffles and pools), and introducing woody debris, because species diversity is positively associated with fire-introduced micro habitats (Manenti, Ficetola, & De Bernardi, 2009; Stephens et al., 2021). We found equivocal results relating to indicator species, which are species selected on the basis of having a measurable, predictable sensitivity to known environmental changes/acute events, whose health and abundance reflect the state of an environment (Carignan & Villard, 2002; Zettler et al., 2013). Noting substantial heterogeneity in the indicator organisms reported, we separately considered "smaller" organisms (where evidence primarily concerned macroinvertebrates) and "larger" organisms (where the most commonly researched organism were fish). This may have been insufficient differentiation between organisms of varying sizes or ecological niches, with mixed results arising from combining species with different degrees of sensitivity to fire.

Water temperature, and conductivity were substantially impacted by fires. Water temperature in particular is considered a key physiochemical measure under the Water Framework Directive of the European Union (Madrid & Zayas, 2007). It interacts with many aspects of water quality such as pH (McCleskey, 2013) and dissolved oxygen levels (Madrid & Zayas, 2007), and substantially moderates the growth of organisms such as algae (L. Wang et al., 2017). We found that bushfires were associated with a notable increase in water temperature, with most measures taking place within one year of the fire.

Bushfire was associated with a marked (average 80%) increase in water conductivity, the capacity of water to pass an electrical current. Relatedly, we found that bushfire is linked with an increase in total ions, and four of the six "major" ions in water - calcium (Ca^{2+}), chloride (Cl^{-}), magnesium (Mg^{2+}), and potassium (K^{+}) (with unclear results for sodium (Na^{+}) - and sulfate (SO_4^{2-}). An increase in conductivity and salt concentration has implications for life and water course morphology. While often necessary for plants, animals and humans in low concentrations (Gregersen, 2021; Kronzucker, Coskun, Schulze, Wong, & Britto, 2013) (Nödler, Licha, Fischer, Wagner, & Sauter, 2011; Shrimanker & Bhattarai, 2020), salination of freshwater systems is toxic to life, can increase erosion, and is difficult to reverse

(Kronzucker et al., 2013; McSorley, Rutter, Cumming, & Zeeb, 2016; Nödler et al., 2011; H. Wang & Zhang, 2019).

The link between fires and post-fire increase in nutrients is well documented (Basso, Mateus, Ramos, & Vieira, 2021). “Nutrients” in water commonly include ammonia (NH_3), nitrite (NO_2^-), nitrate (NO_3^-), phosphate ($PO^{3-}{}_4$), nitrogen (N), phosphorus (P), and dissolved organic carbon (DOC) (Jackson & Williams, 1985; Kirkwood, 1996). Nitrogen is ubiquitous and vital for all life (Follett & Hatfield, 2001). We found a clear elevation (300%) in nitrogen following fire, with some evidence of near immediate recovery to pre-fire levels, but also evidence that elevation could persist for up to three years. The nitrogen cycle includes interconversion between many of the forms of nitrogen through biogeochemical and biological redox processes (Lin et al., 2019). We found marked elevations in key “reactive” forms of ammonia (NH_3) and ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) [4] (Follett & Hatfield, 2001)). The magnitude of the increase was likely inflated by very low pre-fire or control water bodies. We found evidence of an increase in phosphorus and phosphate following fire, though longitudinal evidence indicated a swifter return to baseline, with all evidence three years following fire returning to baseline. Phosphorus (P) is essential for cellular metabolism, photosynthesis, respiration, and growth of plants, and for bone development in animals (Mullins, 2009). Taken together, our findings relating to nutrients indicate the potential for bushfire to be associated with eutrophication, excess plant and algal growth, and depletion of free oxygen promoting hypoxic and acidic conditions in water (Keeney & Hatfield, 2008; Mullins, 2009; L. Wang et al., 2017), although clear evidence of water acidification linked with bushfire is limited.

Dissolved organic carbon (DOC) and iron are important determinants of water colour (Vuori, 1995; Xiao et al., 2015). DOC is the carbon component of dissolved organic matter (DOM; organic compounds that can pass through a 0.45µm filter (Evans, Monteith, & Cooper, 2005)). Iron (Fe) is ubiquitous in freshwater (Vuori, 1995)), and is required by humans, plants and animals (Rout & Sahoo, 2015; Shukla, Tiwari, Pakhare, & Prakash, 2016). Evidence regarding the association between bushfire and DOC, and iron, and water colour was mixed, with half of measures reporting that bushfire had no impact on water colour. This does not align with evidence of fire-related colour change elsewhere (e.g. (Joehnk et al., 2020)). The discrepancy may be due to the scope of the review excluding laboratory-based evidence (e.g. taking ash samples and immersing in controlled conditions off-site). Holden, Chapman, Palmer, Kay, and Grayson (2012) noted that the impact of prescribed burning on water colour

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[4] Note that it was beyond the scope of the review to comment on the other reactive forms, nitric oxide (NO) and nitrogen dioxide (NO_2) and nitrous oxide (N_2O).

was detectable in laboratory plots, but not in catchment studies, and note that greater dilution and draining in catchment contexts may explain the difference.

We did not find clear evidence that bushfire contributed to water "hardness". Evidence surrounding toxic heavy metals, including mercury (Hg), lead (Pb) and cadmium (Cd) was unclear. Evidence was similarly mixed for polycyclic aromatic hydrocarbons (PAH), organic compounds of varying sizes characterised by fused aromatic carbon rings (Manoli & Samara, 1999) generated by incomplete combustion of organic materials in both anthropogenic and natural combustion processes, such as fossil fuel burning and bushfires (Abdel-Shafy & Mansour, 2016; Guo et al., 2007). This is likely due to the situation-specific sources of these contaminants, such as drinking water storage (Spinks, Phillips, Robinson, & Van Buynder, 2006), and industrial waste (Manoli & Samara, 1999).

It should be noted that the weight of evidence reported reflects what has been most studied, hence evidence for factors such as nutrients (which are ubiquitous, vital for life, and closely tied to both ecosystem health and anthropogenic activity (Follett & Hatfield, 2001; Keeney & Hatfield, 2008; Lin et al., 2019)) is substantially more numerous than evidence for factors with niche or situation-specific interest, such radionuclides (which are most likely to be tied with contamination from uncommon human infrastructure, such as the Los Alamos National Laboratory, USA, as explored in (Gallaher & Koch, 2004)). Relatedly, an important omission is Indigenous knowledge. Within the manuscripts identified systematically, and with additional targeted searching, the authors found examples of Indigenous-led research on fire management (e.g. (Neale, Carter, Nelson, & Bourke, 2019)) and water management (e.g. (Wilson, Mutter, Inkster, & Satterfield, 2018)), but were unable to find manuscripts linking bushfire to water with clear input from an Indigenous perspective. The partnership with the Indigenous (Mogo) Local Aboriginal Land Council that underpins this research has offered deep insights into the cultural knowledge that exists on the impacts on fire on water. in agreement with Fletcher, Romano, Connor, Mariani, and Maezumi (2021), we strongly advocate for future research in this area to foster the interaction between diverse epistemologies to achieve greater productivity and conceptual advances, and consequently argue the importance of integrating Indigenous perspectives into the framing, conduct, and interpretation of research regarding bushfire in Australia.

The high-level overview of the current state of evidence provided by this review is both a strength and a weakness. This condensed summary of the impacts of bushfire on water is intended to provide context for future investigations on this topic, both by giving context to research focused primarily on physical, chemical, and biological factors, and serving as an index that could be used to augment literature review. However, the required degree of abstraction to achieve this summary obscures many differences in the specific characteristics of each fire event (e.g. intensity and duration), water body context (e.g. surrounding hillslopes, rainfall patterns), and measurement. The inability to comment on the possible role of fuel type in the relationship between fire and water in this review due to data sparsity demonstrates that a larger body of evidence will be required to meaningfully address these differences in future. Relatedly, this review highlighted substantial heterogeneity in measurement approaches and study timing (relative to fire events). An example of the importance of timing is where the same authors used the same measures and applied similar analyses regarding the impact of the 2002 Hayman fire on Cl^- in catchment water. Evidence was different when measures were taken at summer, winter or snowmelt (with significant association found only in summer (Rhoads, Entwistle, & Butler, 2006)), and later unclear in a later study across more streams across a longer period of time (Rhoades, Entwistle, & Butler, 2011). The diversity in measures for many of the physical, chemical and biological parameters discussed may reflect differing end points of interest, that is, drinking water quality considerations versus ecosystem change/environmental considerations.

Conclusion

The results of this review reinforces Smith et al. (2011)'s contention that the impact of bushfire on water is multivalent, interactive, and complex. Some of the focal factors, such as water temperature and conductivity, were consistently increased following a fire, others such as particle size and species diversity were consistently decreased following fire, while the balance of evidence for many was mixed. Evidence focused on largely short to medium term impacts (e.g. within 2 years of the fire event) on physical, chemical, and biological characteristics of water, with only a subset of studies reporting on longer term changes in response to fire. There was also evidence of resilience and recovery. We urge future work to consider measures that will fulfil both environmental and human health considerations, to allow more integrated insight into the impacts of fire on water.

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Supplementary materials

1. Justification of review approach, and aim

The fire history of a landscape is the extent, severity, intensity, frequency, type (controlled/prescribed versus uncontrolled) of fires, and the characteristics of that landscape such as slopes, soil type, vegetation, and the geomorphology of watersheds and the bodies of water themselves (Bixby et al., 2015). Much research into the impacts of fire distinguish between controlled and uncontrolled fires (Bixby et al., 2015). Although all fire undergoes common physical processes and the history of these ‘types’ of fires in any given landscape is somewhat intertwined (Sayre, 2007), uncontrolled fires tend to be more widespread, intense, and related to other relevant environmental factors (such as prolonged drought). Accordingly, this review will focus on uncontrolled fires (including controlled fires that became out of control).

One of the more salient factors linking this history to any given fire event is the accumulation of fuel, “biomass which contributes to the spread, intensity and severity” of a fire (Arroyo, Pascual, & Manzanera, 2008, p1240). While overall amount of fuel can be highly predictive of fire likelihood and intensity (Sharples et al., 2016), the type of fuel is also consequential. The broad concept of “fuel” can be decomposed into meaningful categories by examining how different aspects of particular fuels can be linked to predictable fire behaviour (Merrill & Alexander, 1987). Such classification is complex, and highly site-specific (Arroyo et al., 2008). For the purposes of this review, and in particular to explore whether Australian bushfires may have a characteristic impact on water, we arrange fuel type according to a synthesis of European (Europe, 2011), American (Andrews, 1986) and Australian guidelines: dominant vegetation landscape (grassland, shrubland, forested), and dominant tree (eucalypt, other evergreen, deciduous, or mixed). This scheme reflects the fact that primarily eucalyptus forests, as found natively in Australia, the Philippines and New Guinea (Paine, Steinbauer, & Lawson, 2011) and historically imported and established in places such as California (Groenendaal, 1983), Ethiopia (Pohjonen & Pukkala, 1990), and Portugal (Catry, Moreira, Tujeira, & Silva, 2013), produce ash distinct from that found in other forest types (e.g. higher pH, electrical conductivity, higher levels of boron and sodium; see table 2 in (Harper et al., 2019)).

It is also important to understand the immediate impacts of bushfire alongside the longer-term effects (Bixby et al., 2015). Some immediate factors influencing water quality (such as acute variation in water temperature (Hitt, 2003)) – can attenuate quickly, while others (such as longer-term increase in water temperature due to loss of vegetation that provided shade over water (Mahlum et al., 2011)) only become apparent in following months and years (Minshall et al., 1997; Moody et al., 2013). These factors are a complex, landscape-specific, and interact with one another. The most holistic considerations include fuel type and management, the nature of the fire itself (most notably, heat and duration) and thus subsequent landscape denudation, ash deposition, and hydrological and erosional processes (Bodí et al., 2014; Nunes et al., 2018; Robichaud et al., 2009).

While much of the literature focusses on mobilisation of ash and debris arising from the fire itself (e.g. Balfour et al., 2014; E. C. Oliveira-Filho et al., 2018), large bushfires can also increase sediment erosion and runoff in the existing soil to an extent comparable to anthropogenic land clearing and logging (Cannon et al., 2001; Richardson et al., 2018; Robichaud et al., 2009). This can change the geomorphology of waterways themselves on a long-term basis (Holloway et al., 2020; Jung et al., 2009; Shakesby & Doerr, 2006). Fires can also alter the biogeochemical properties of the soil on a long-term basis, which has implications for vegetative regrowth, and chemistry of how subsequent soil runoff impacts water quality (Abraham, Dowling, & Florentine, 2017; Ferreira, Coelho, Boulet, & Lopes, 2005; Minshall et al., 1997).

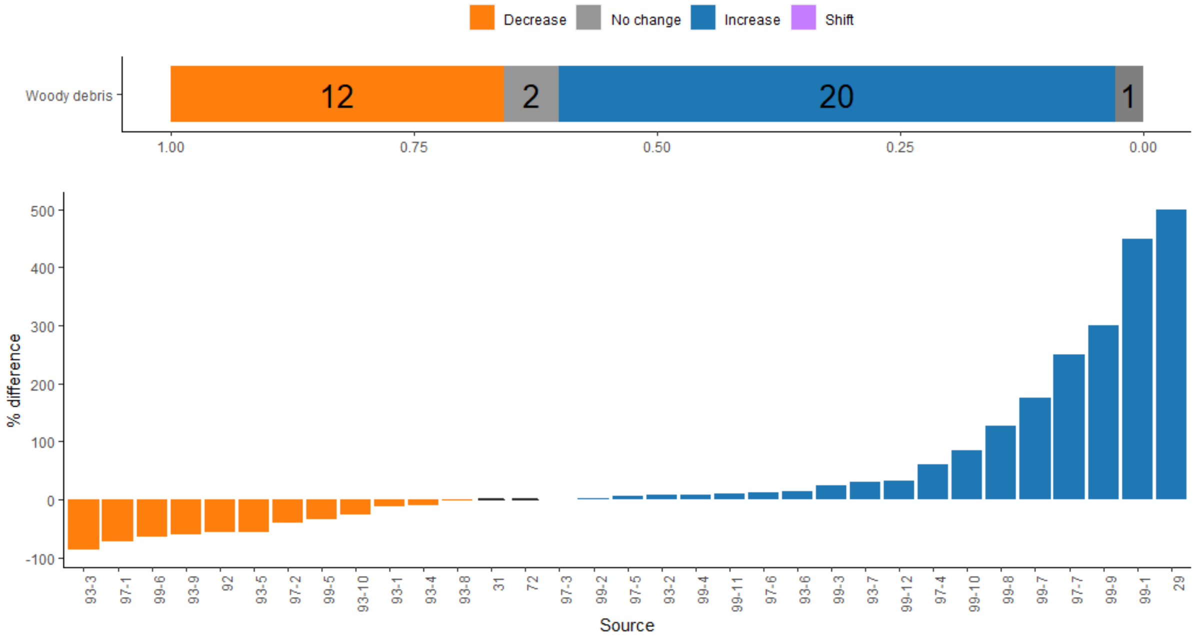
Despite substantial heterogeneity in the available information, synthesis to some extent exists in excellent conceptual models, such as Bixby et al.'s path diagram linking fire to outcomes in ecosystems within streams (see figure 1, p1341 of ((Bixby et al., 2015)), and large, in-depth reviews of topics such as (Abraham et al., 2017)'s work on post-fire metal mobilization into water. These reviews are comprehensive within a particular scope (e.g. ecosystem health and metals respectively), but do not provide a cross-sectional account of the immediate through long-term impacts bushfires can have on water in context. Despite calls for a holistic view of water quality in Australia that includes biological, chemical, and physical, metrics (Norris & Morris, 1995), to our knowledge, to date there are only two manuscripts encompassing a breadth of factors (e.g. sediment, nutrients, trace elements, pollutants, toxicity, and more). These are Smith et al. (2011)'s exceptional narrative review on fire effects on water quality in forest catchments, and the study of the impact of fire on a single site, Earl and Blinn (2003)'s exploration of the impact of ash on Gila River drainage. There is scope to build on this work by taking a systematic approach and expanding the breadth of indicators to explicitly include the hydrological and geomorphological effects of bushfire on water. The aim of this review was to establish a comprehensive overview of the changes occurring in fresh waterways following bushfires. While global data was included and discussed, interpretation focused on the Australian context where appropriate.

2. *Measure-by-measure plots including further detail*

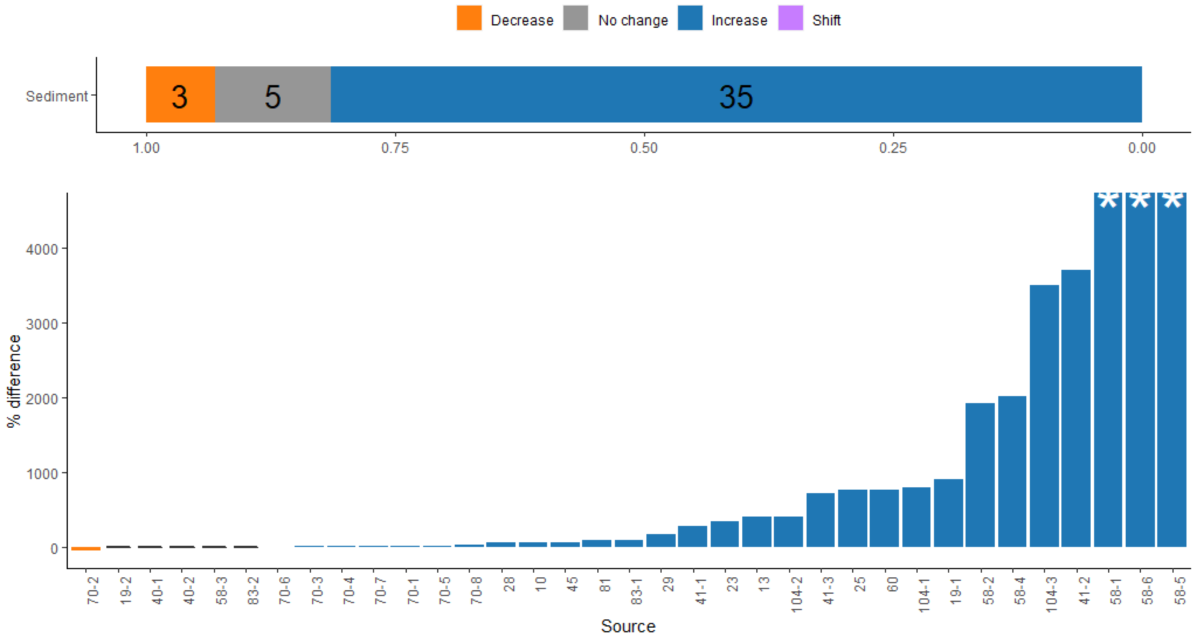
In the following figures, the major panels summarise evidence from the first measure following the fire. “Increase” and “Decrease” is a composite of measures relative to pre-fire measures in the same water body, and relative to matched controls. “Shift” indicates some change that cannot be quantified in terms of increase or decrease of a specific number. The upper panel summarises all evidence, while the lower panel displays evidence where precise numbers were reported. Numbers on the "source" axis correspond to publications and further information provided in the supplementary results table. White stars and the peak of counts indicates axis truncation included to enhance the legibility of the other measures: see supplementary results table for precise values.

Where longitudinal data is available, two additional plots are added to the right. The upper right panel situates when data was collected, with joined points indicating multiple measures from the same study. The lower right panel indicates reported change over time, where “returned” indicates a return to pre-fire or control levels, and “still increased”, “still decreased”, or “no change” indicate that impact detected at the first measurement persists. Numbers on bars indicates the count of manuscripts providing evidence in this direction.

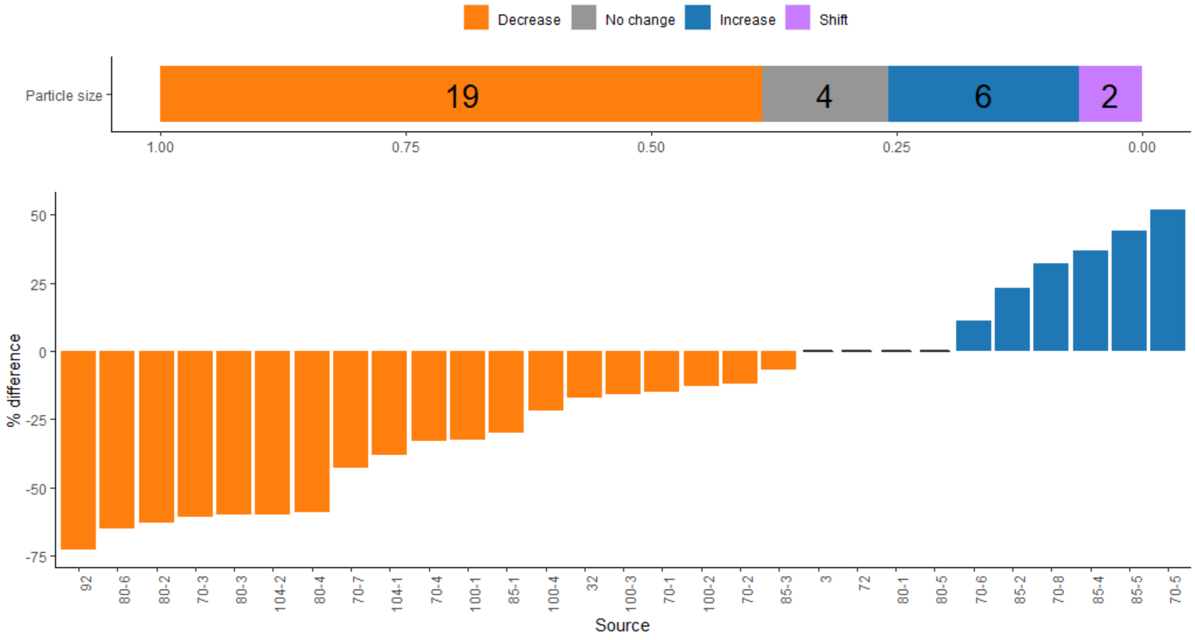
Woody debris



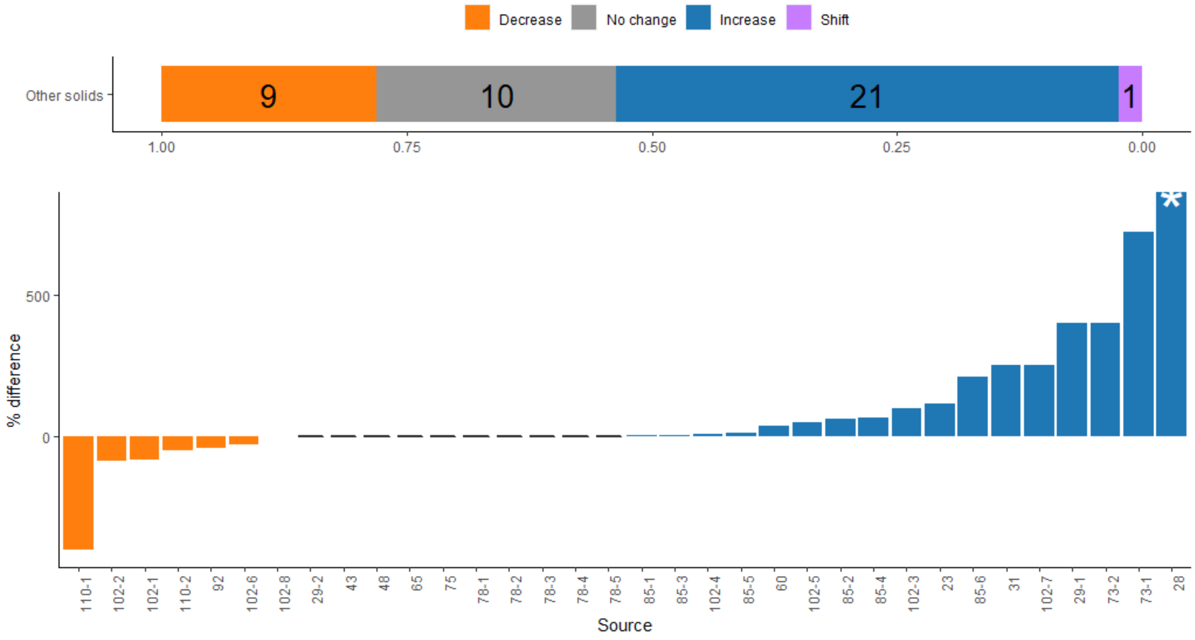
Sediment



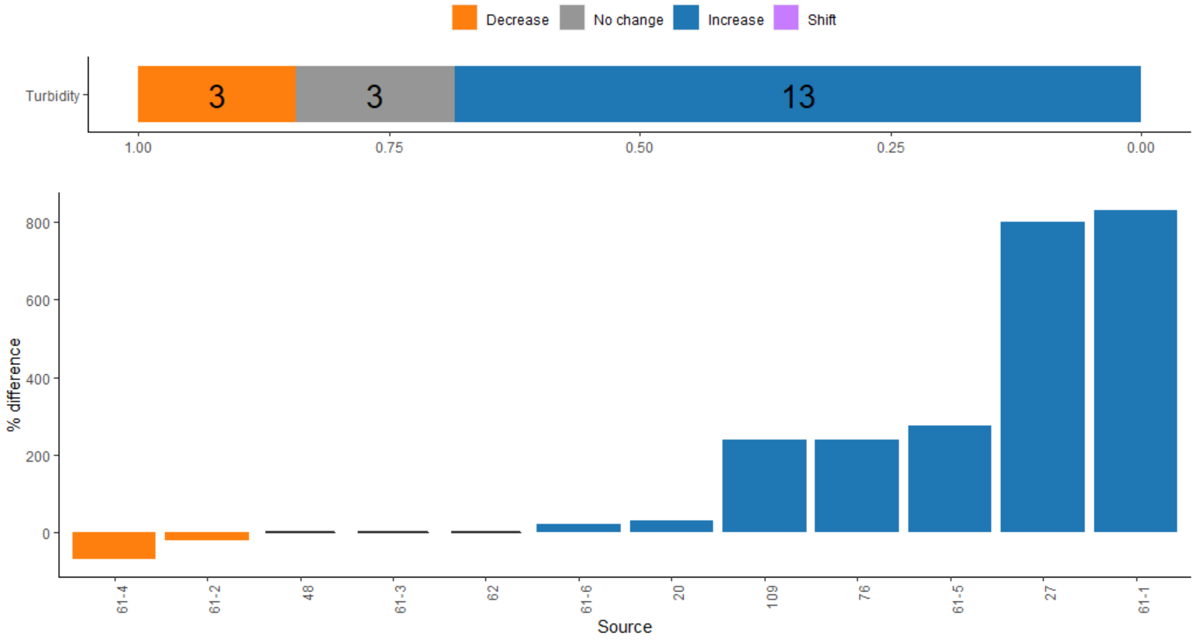
Particle size



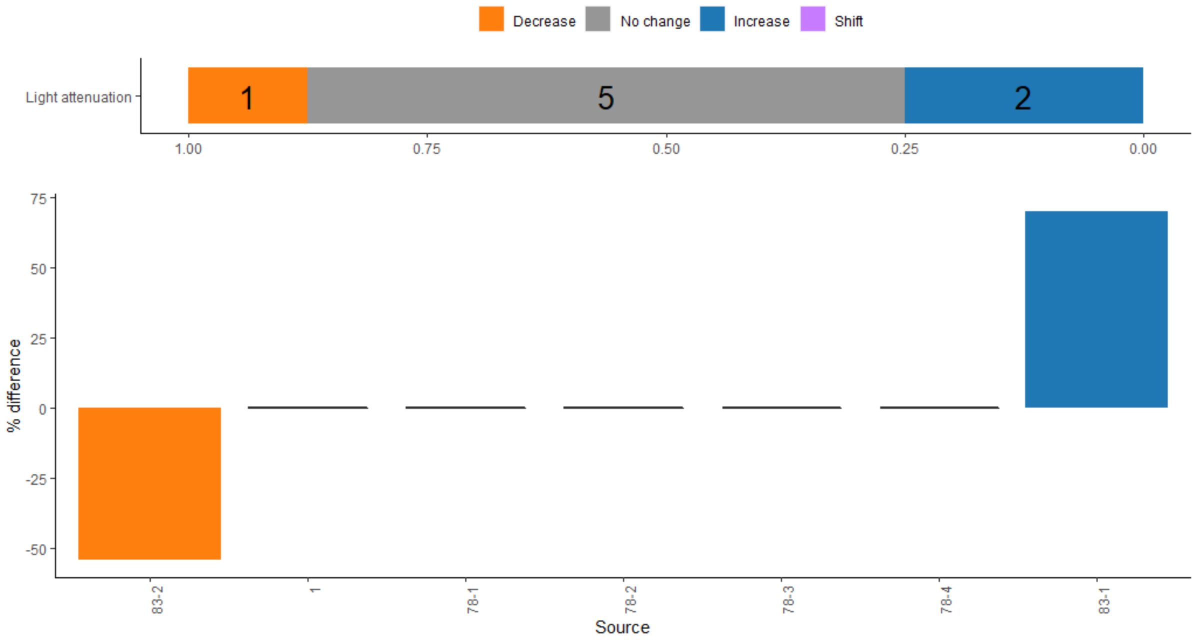
Other solids



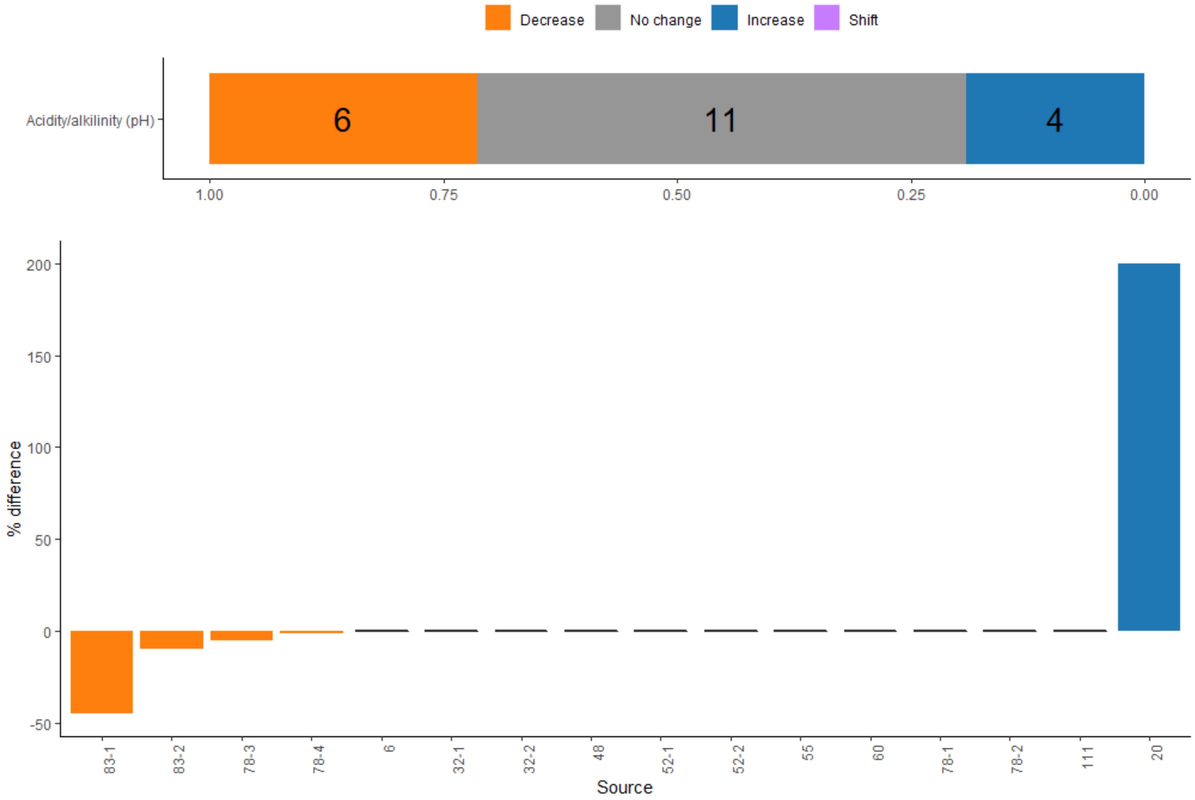
Turbidity



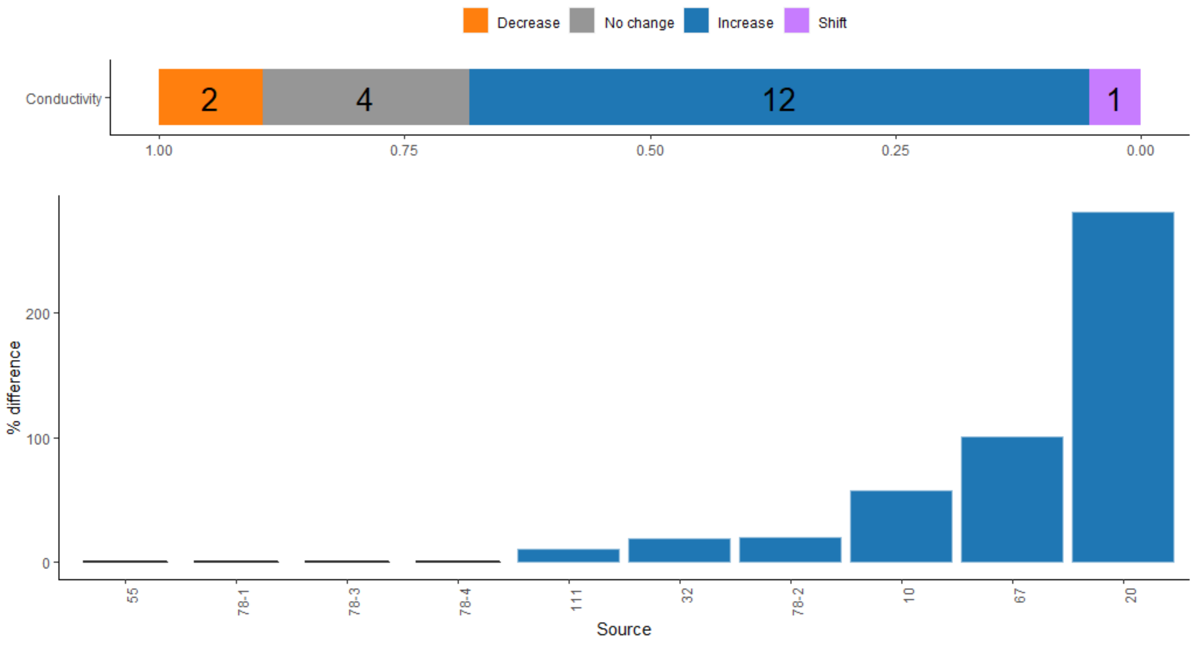
Light attenuation



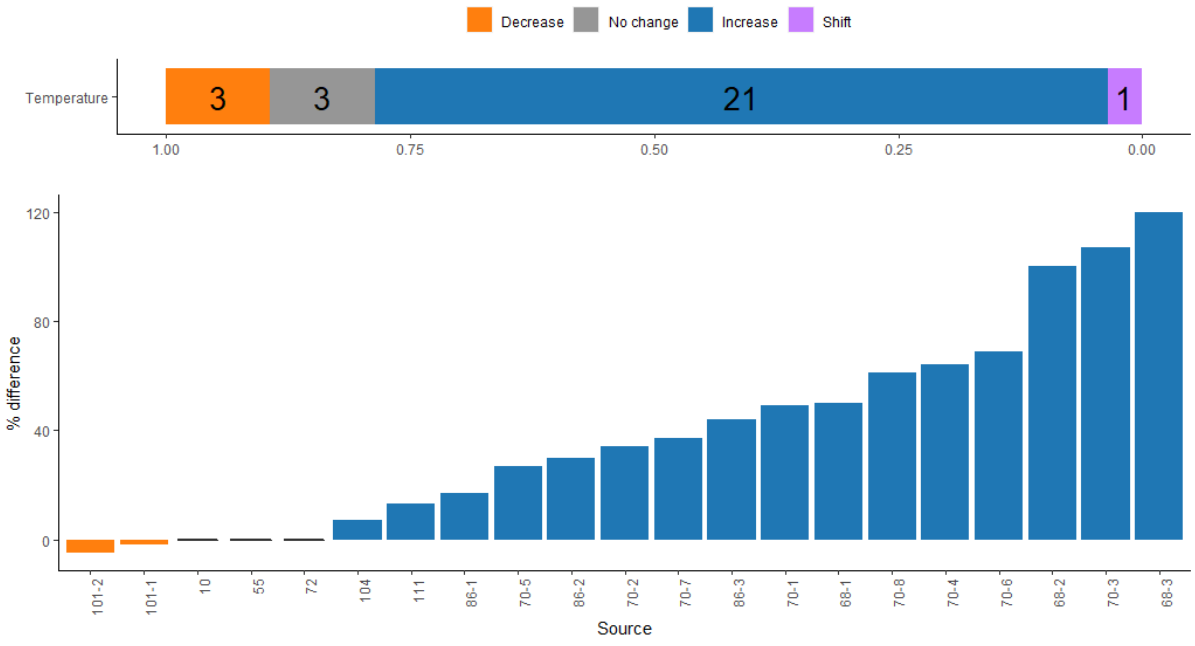
Alkalinity (pH)



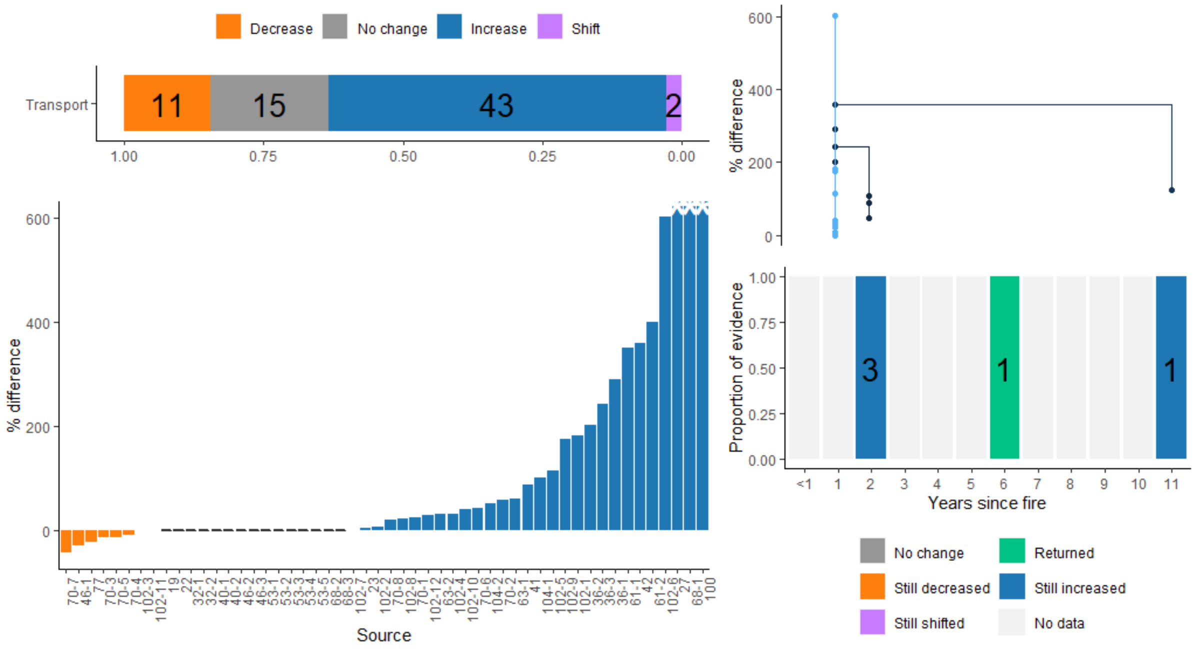
Conductivity



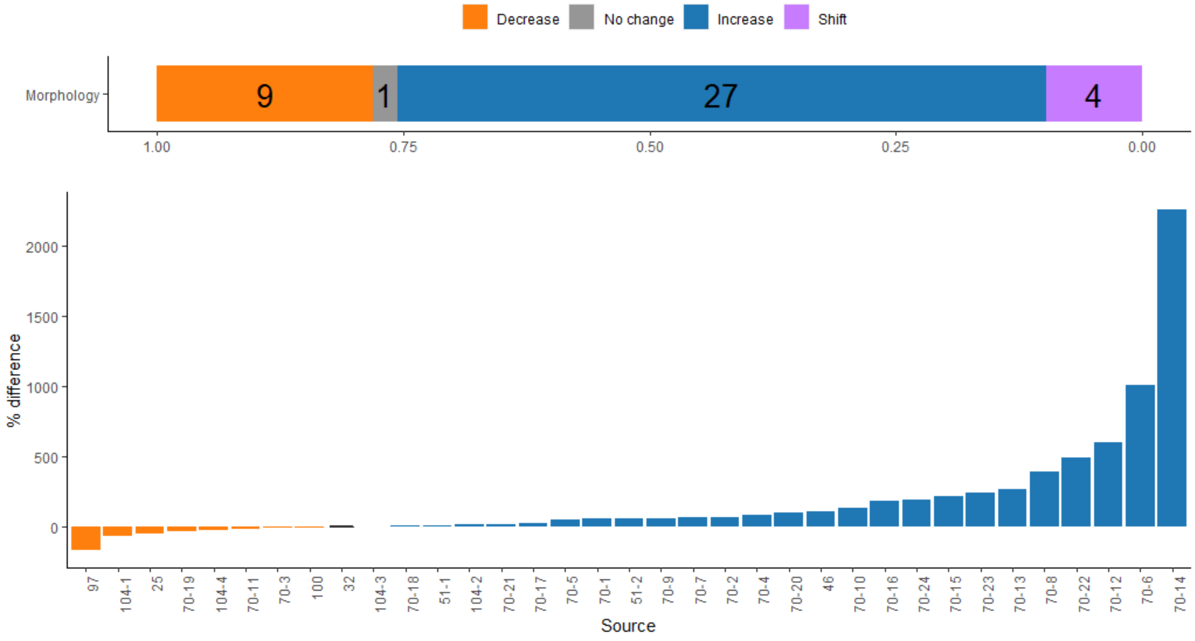
Temperature



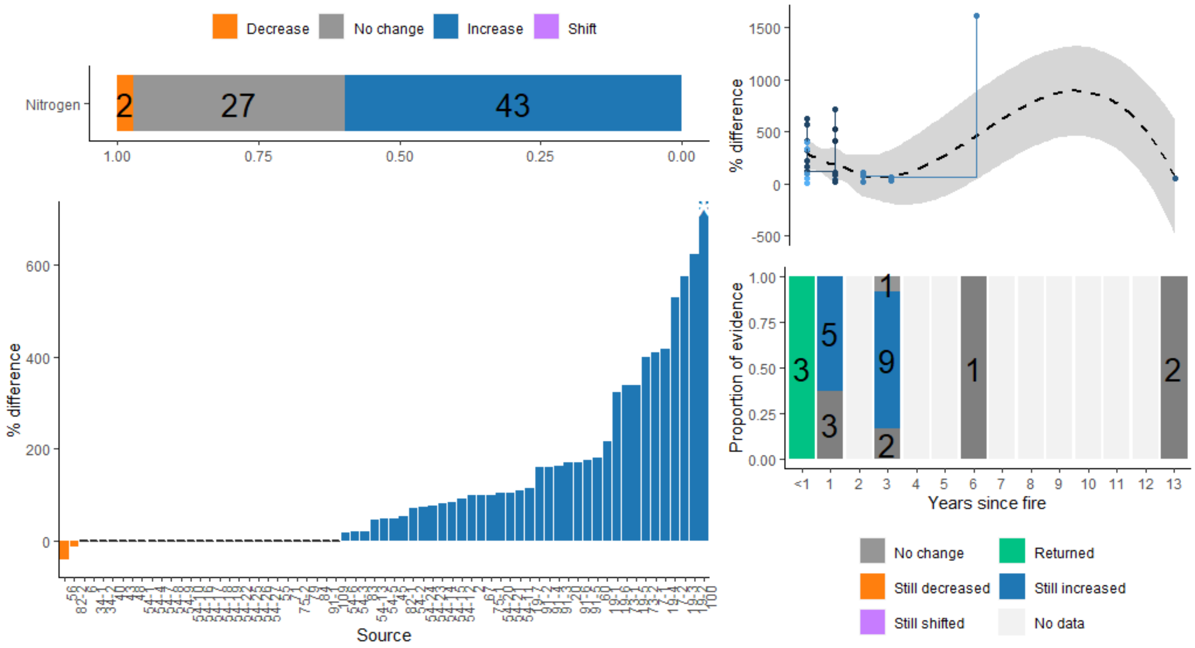
Transport



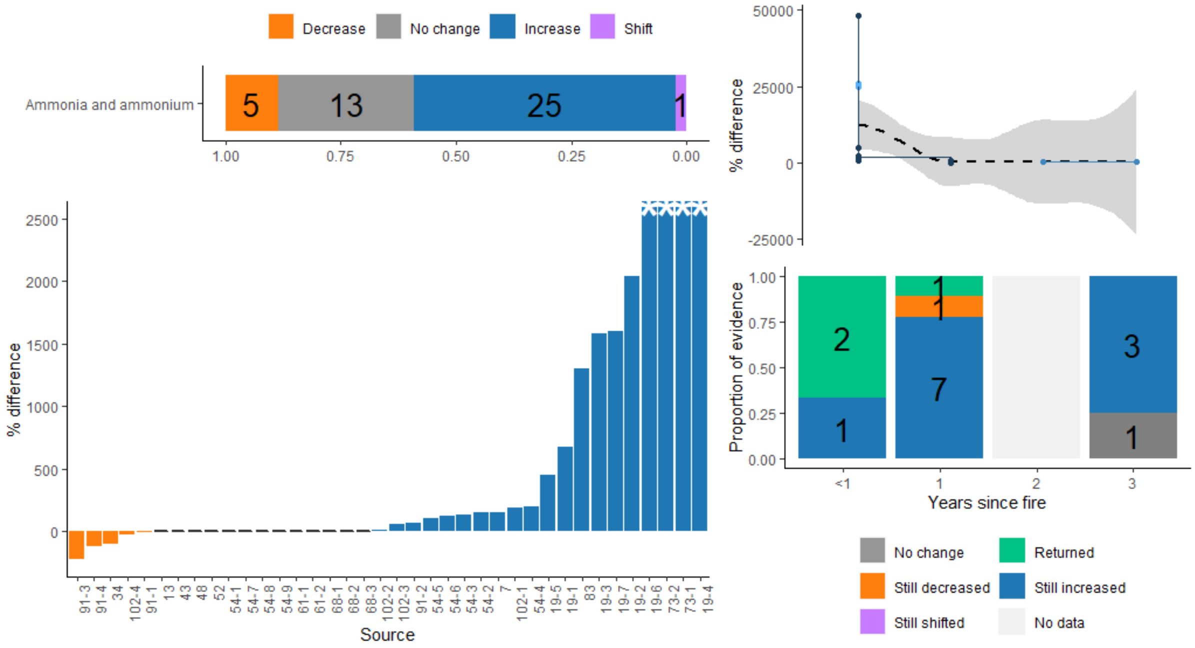
Morphology



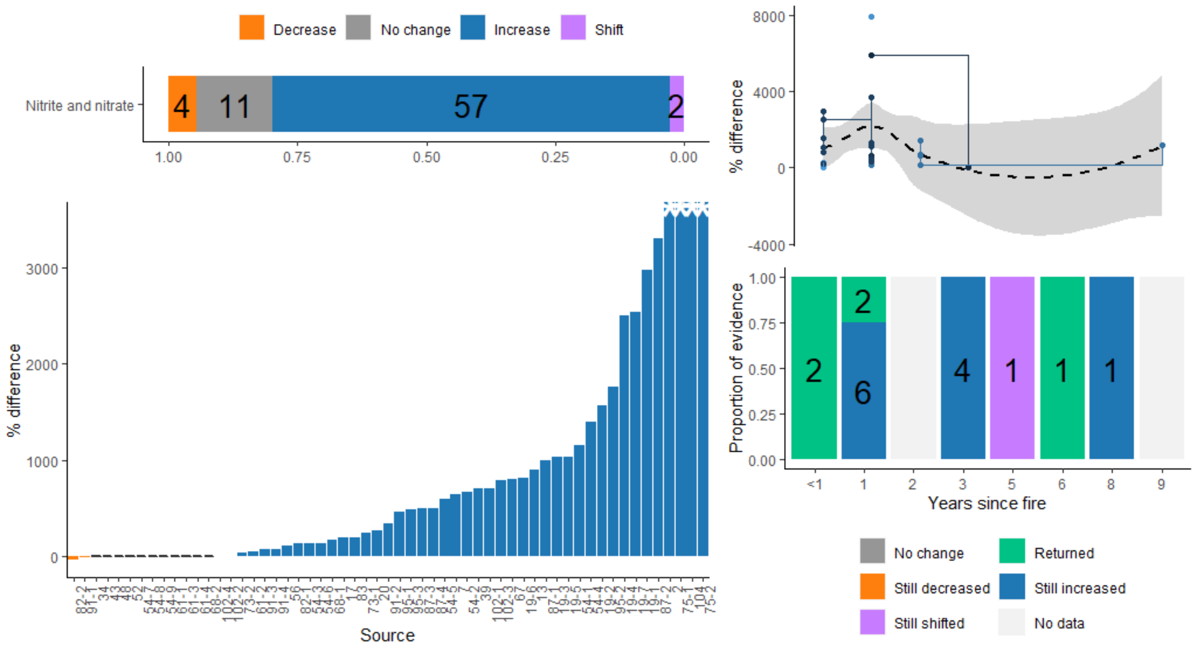
Nitrogen



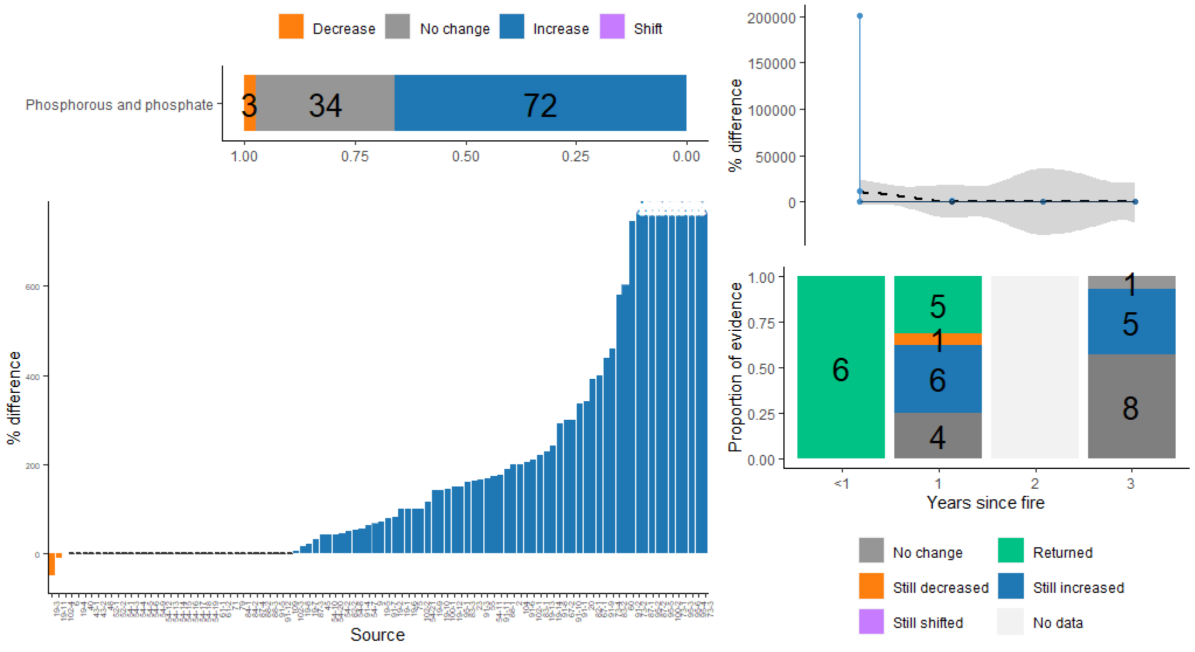
Ammonia and ammonium



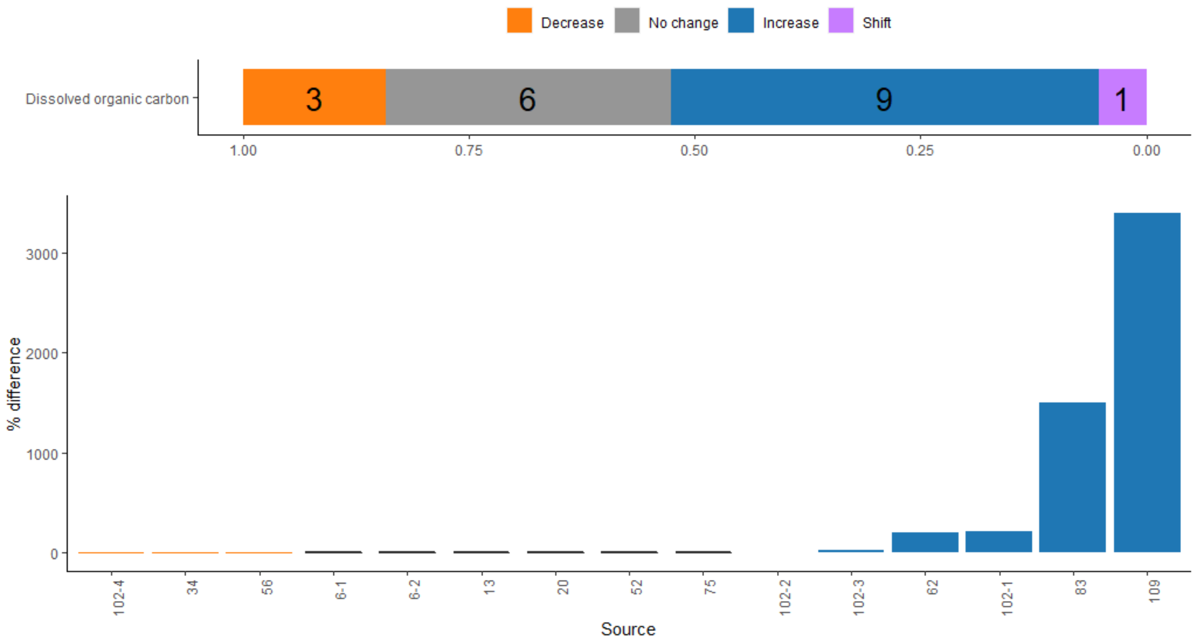
Nitrate and nitrite



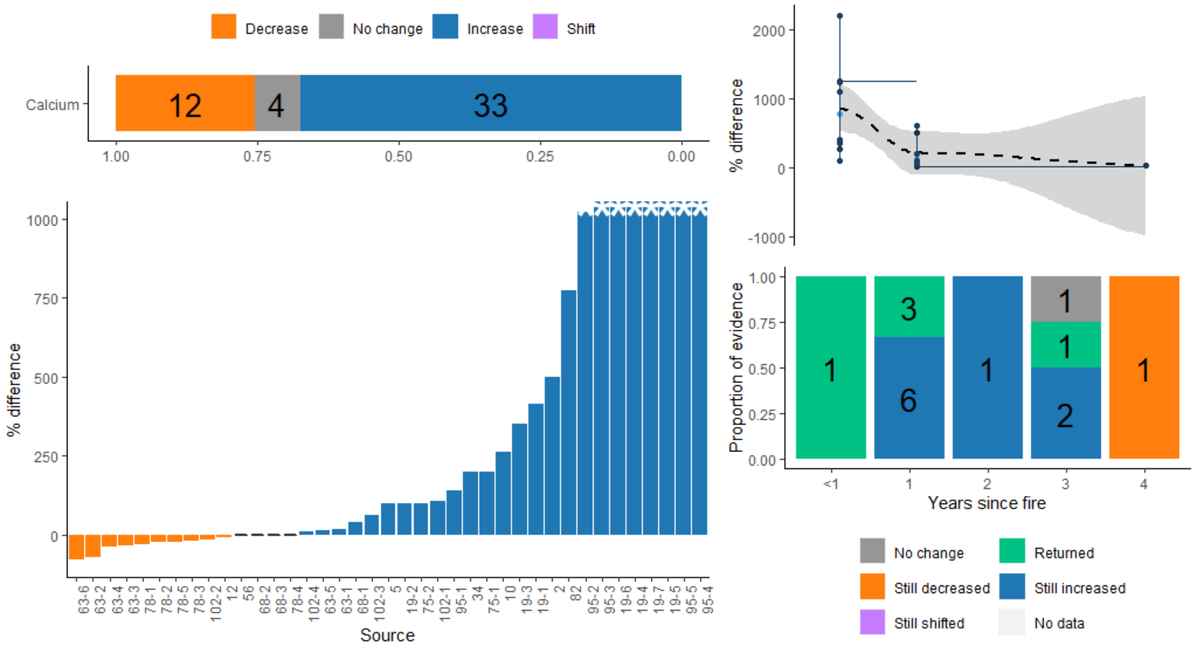
Phosphorous and phosphate



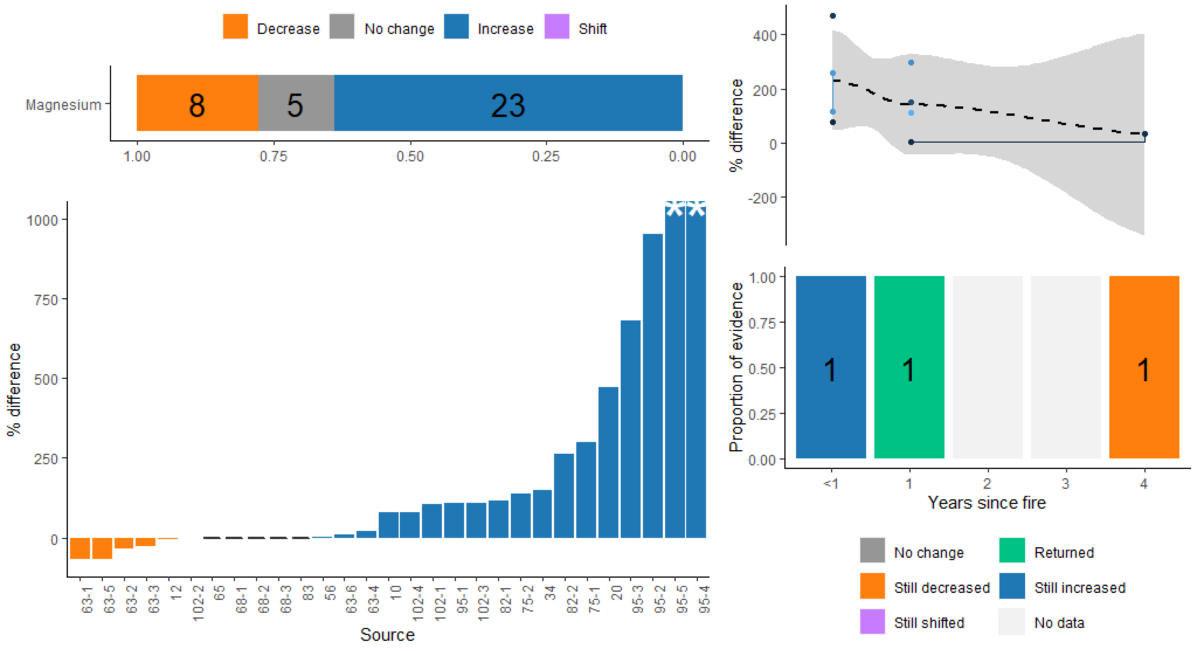
Dissolved organic carbon



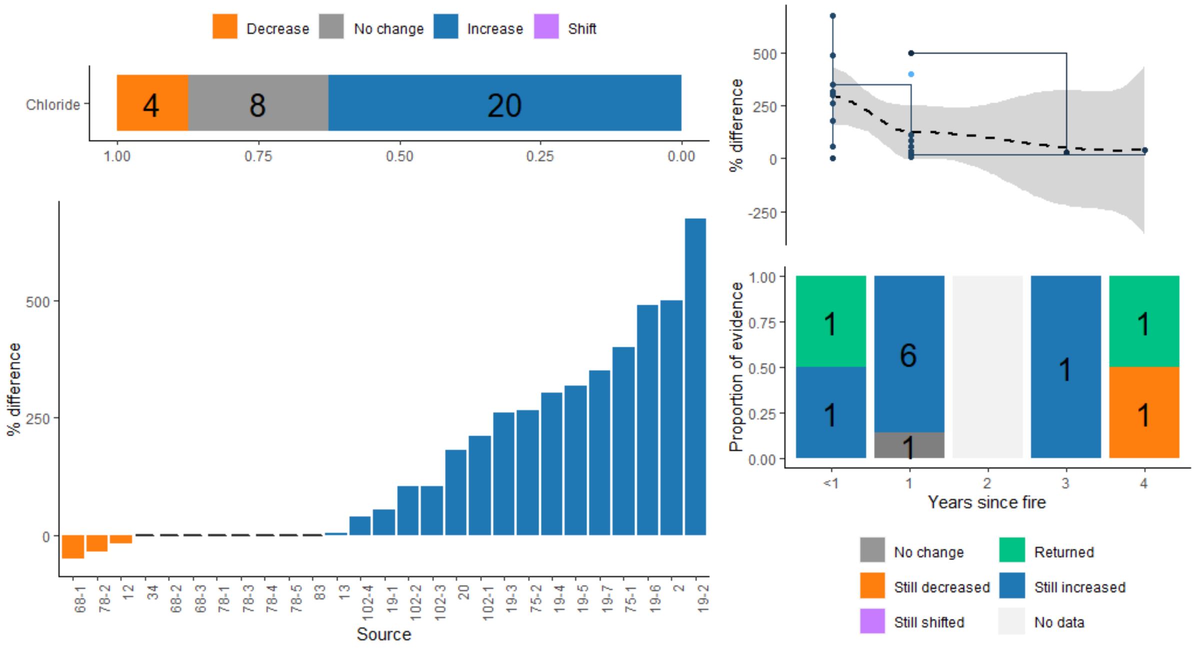
Calcium



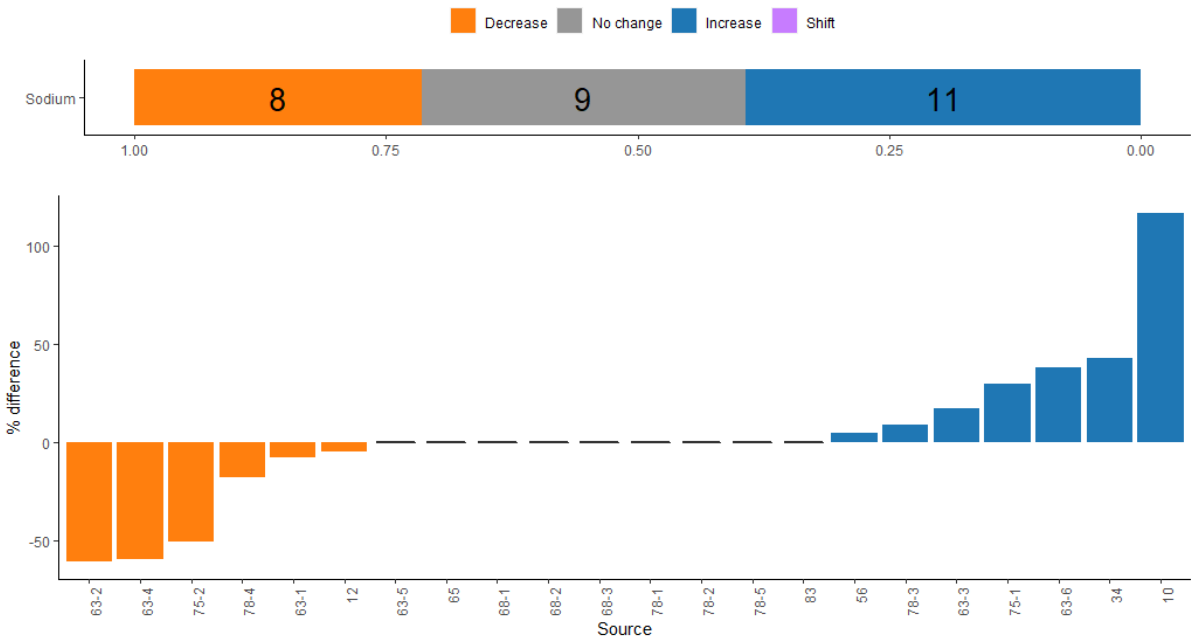
Magnesium



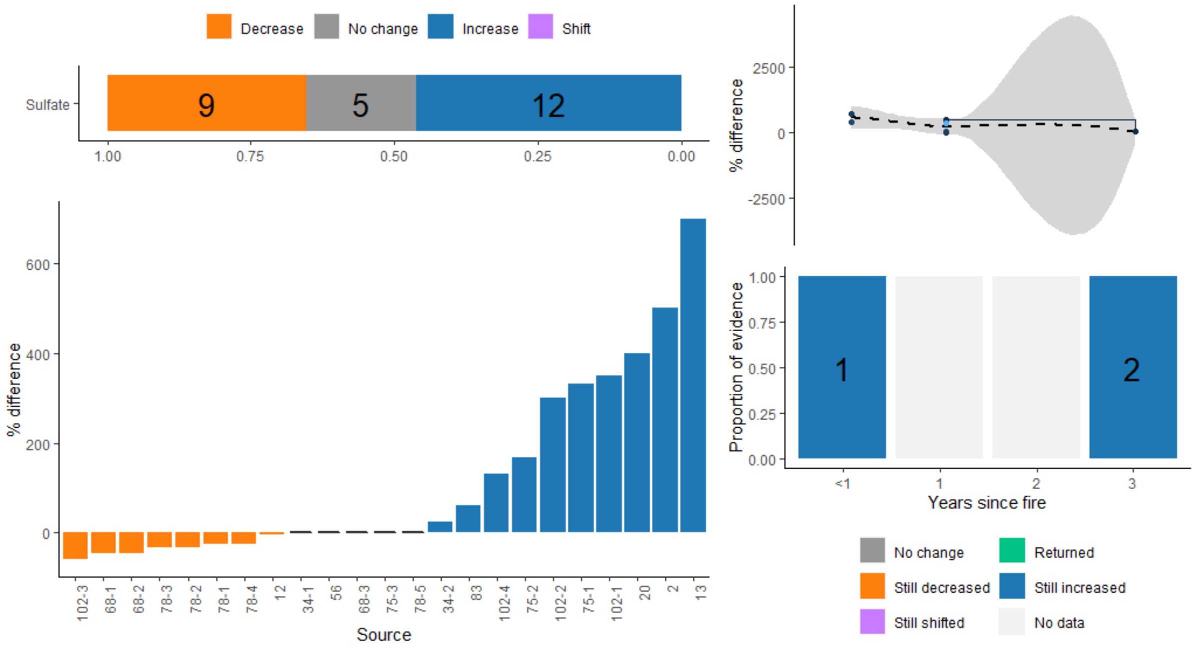
Chloride



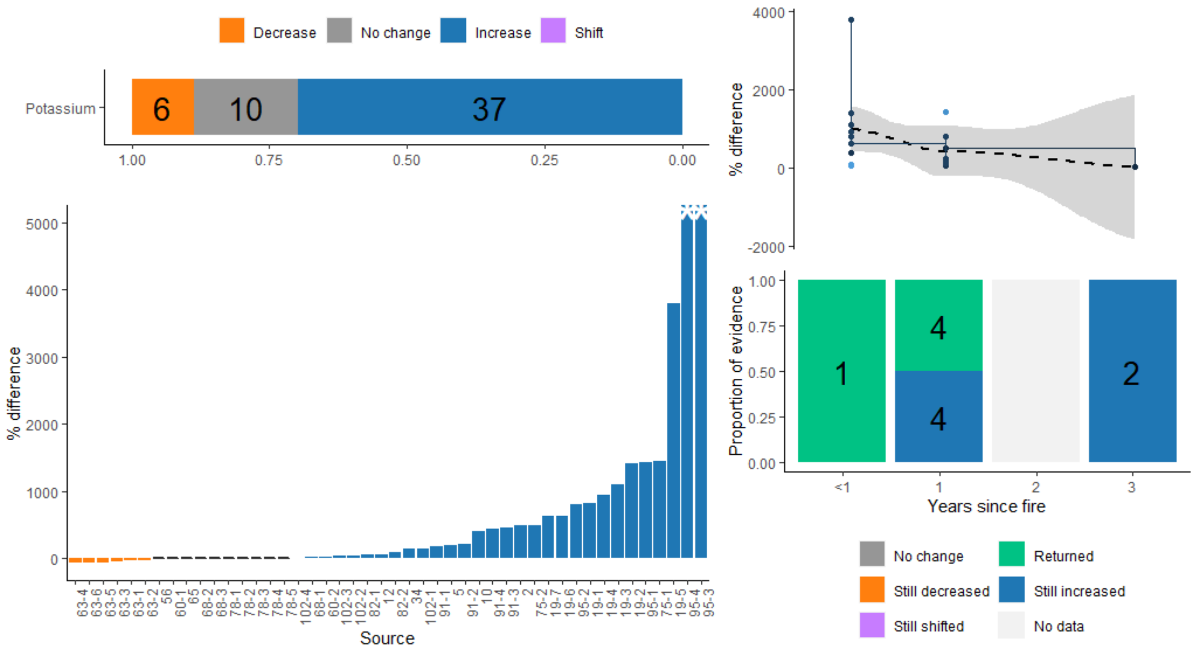
Sodium



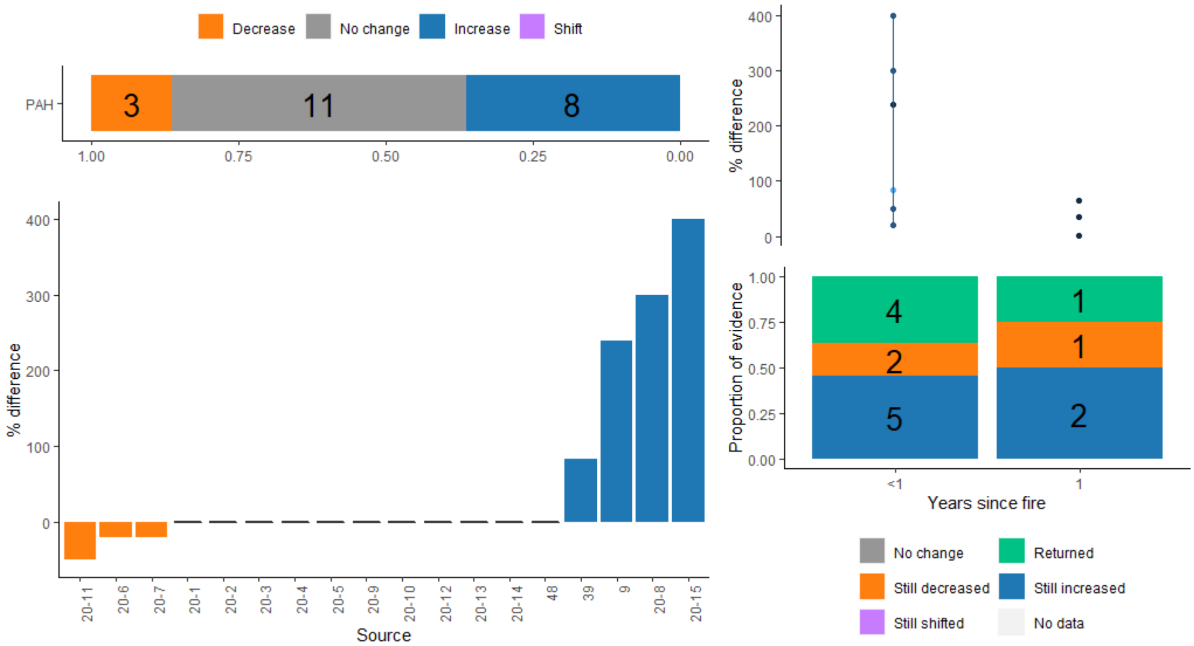
Sulfate



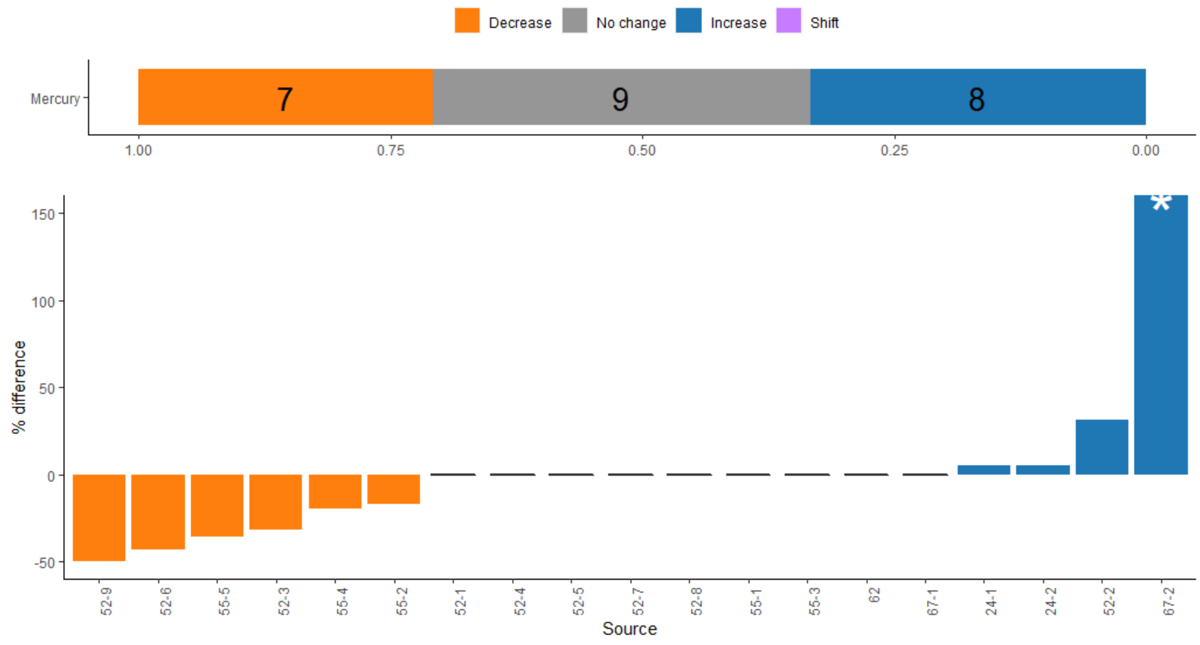
Potassium



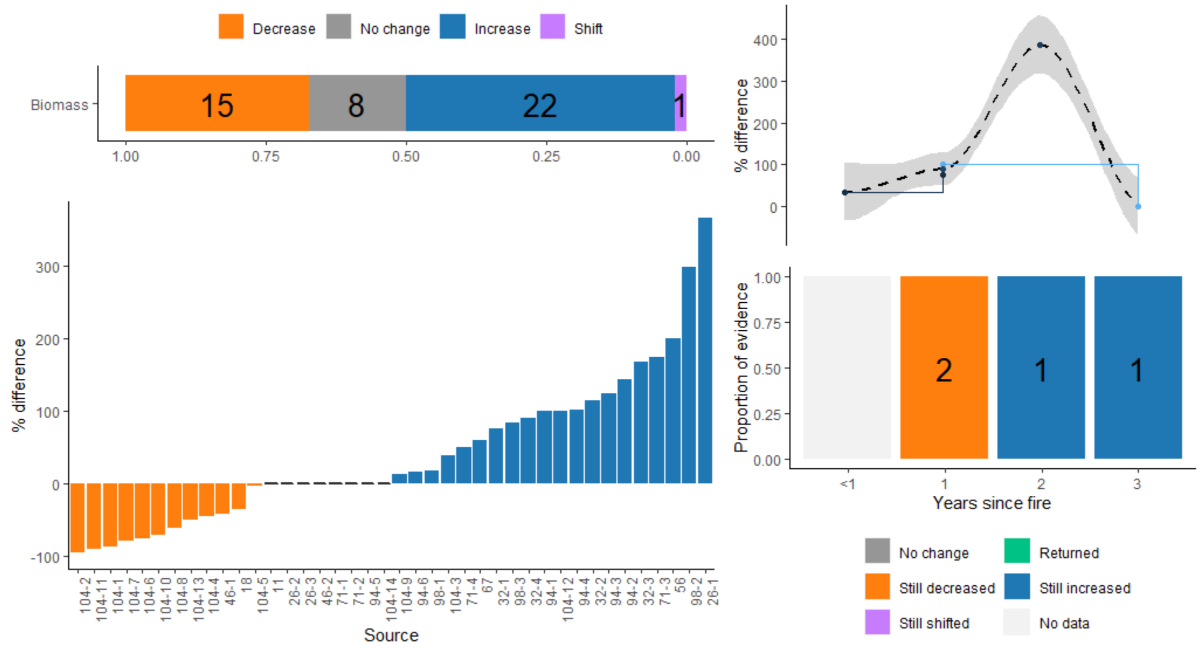
Polyaromatic Hydrocarbons



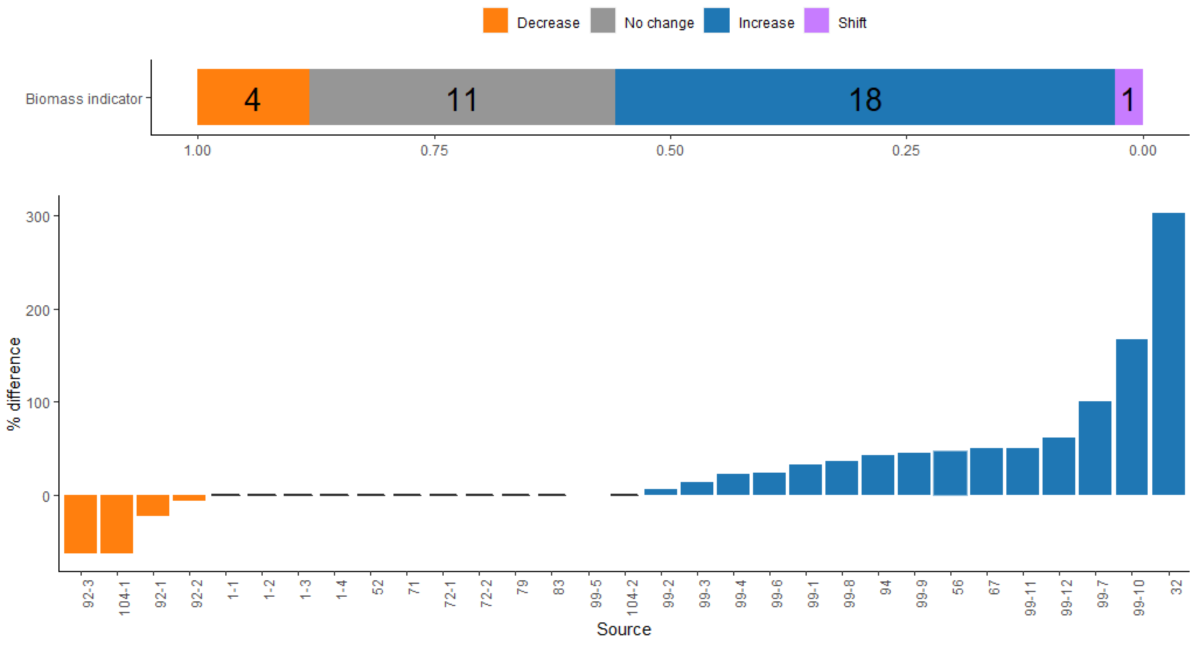
Mercury



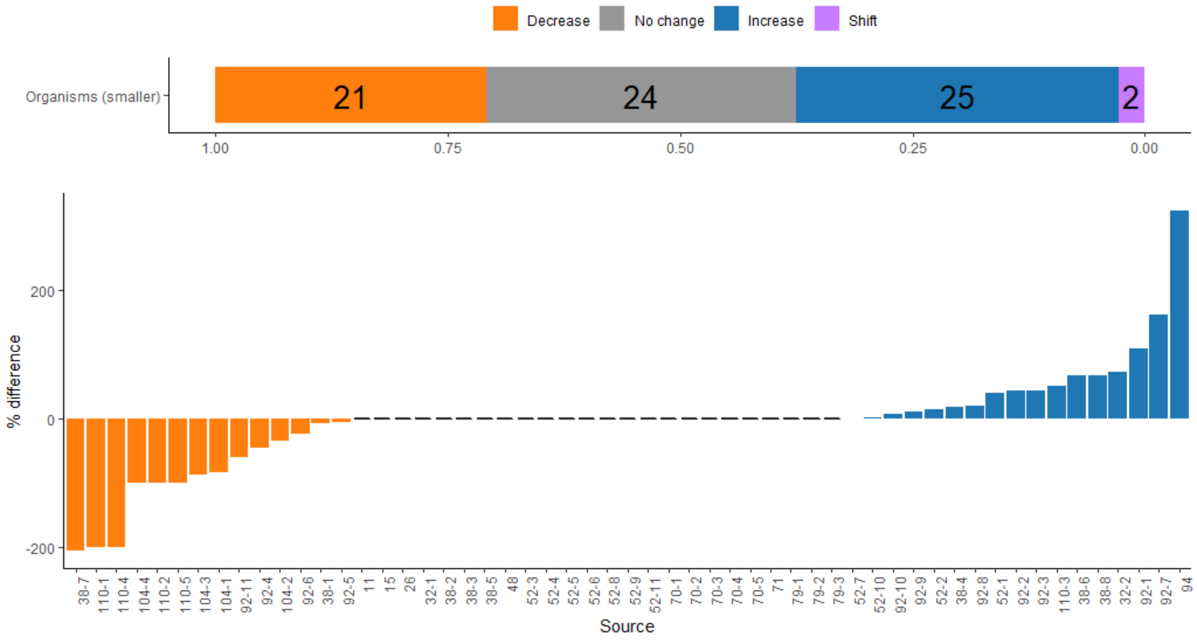
Biomass



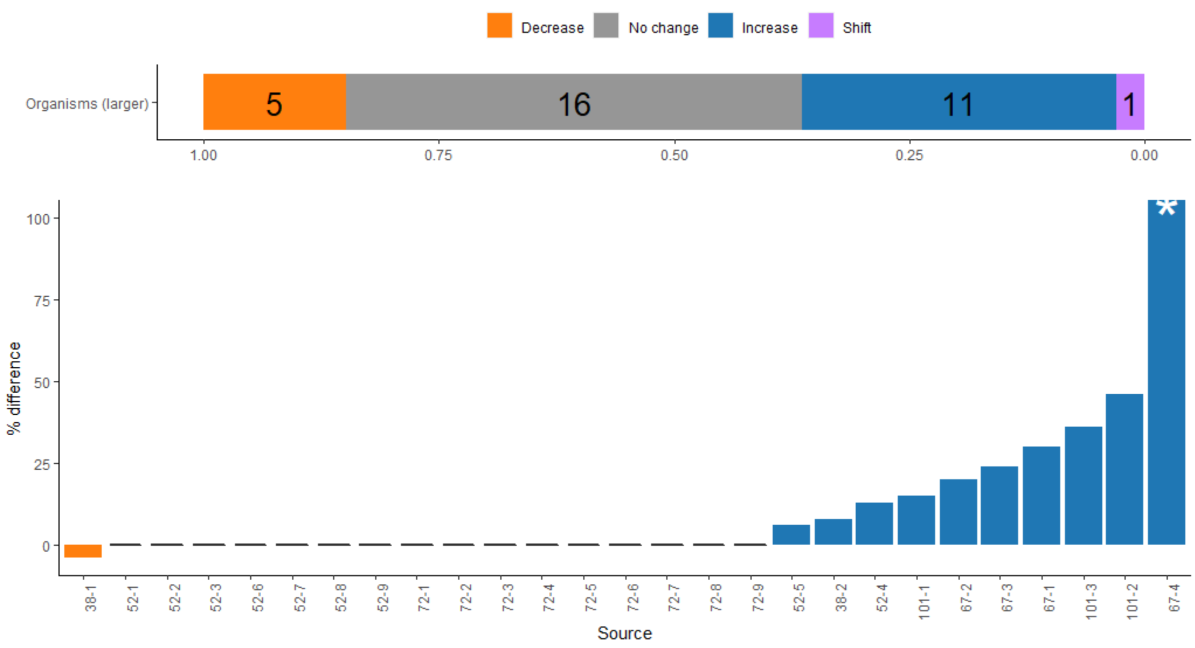
Biomass (indicators)



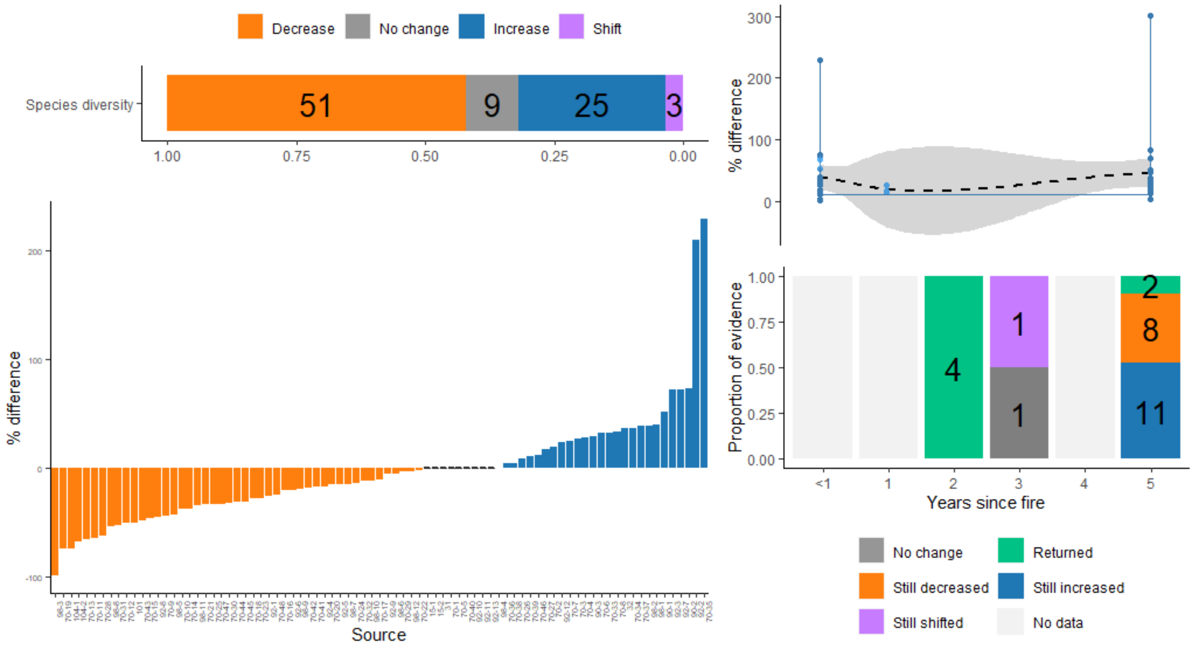
Organisms (smaller)



Organisms (larger)



Species diversity



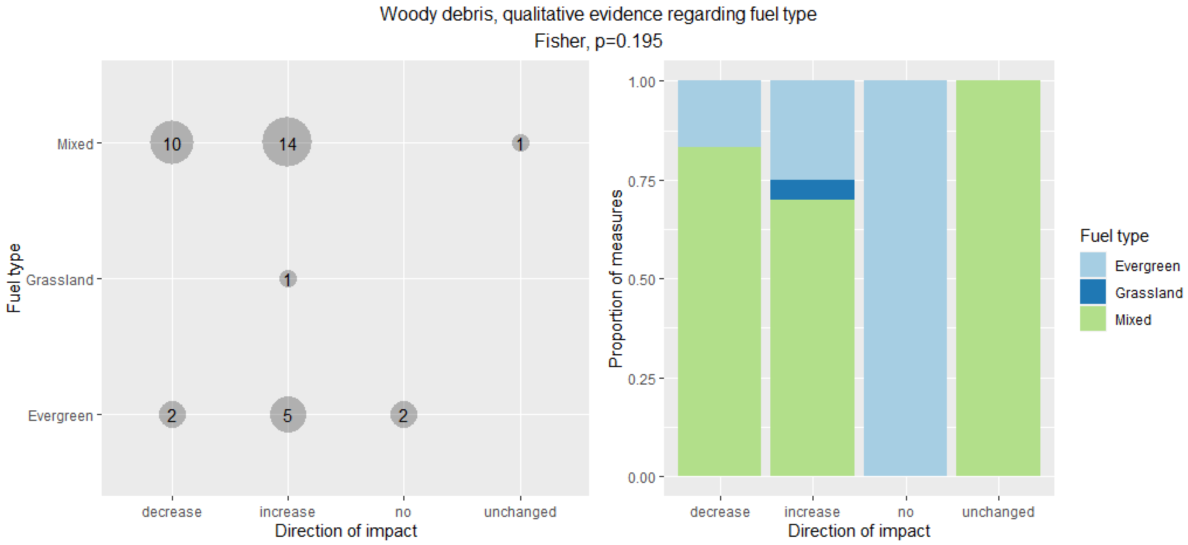
3. Measure-by-measure plots of fuel type

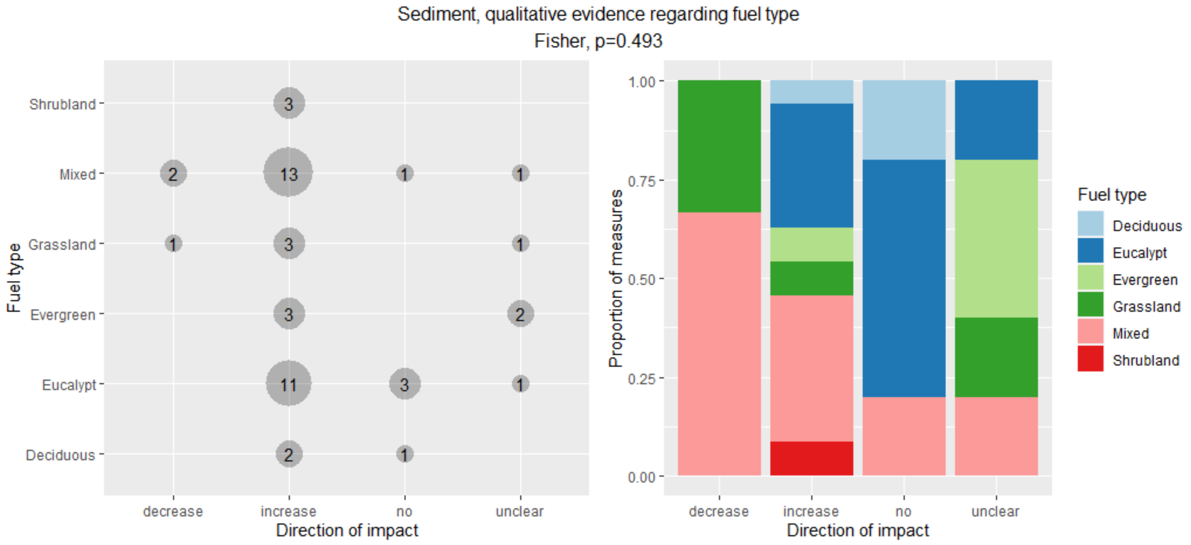
The following plots summarise the count of measures providing qualitative evidence of fire impact (increase / decrease / no change / unclear evidence) by fuel category type (grassland / shrubland / eucalypt / other evergreen / deciduous / mixed). The title indicates whether a statistical test was carried out on the following basis:

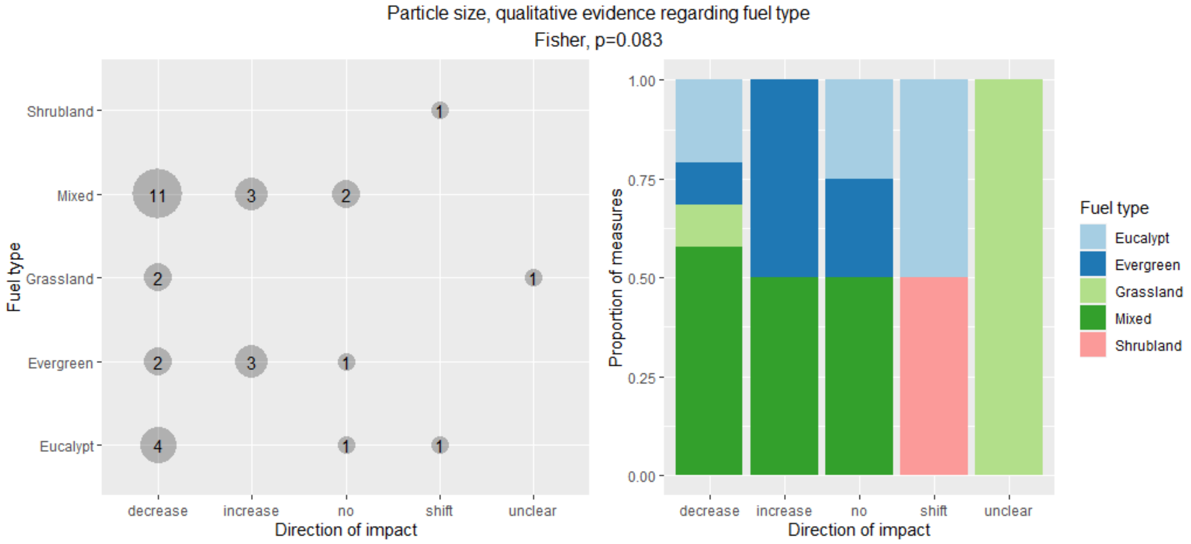
- No statistical test if there are fewer than 5 datapoints in total, or only one category (thus no comparisons can be made)
- Fisher's exact test (with Monte Carlo simulated p value at 10,000 replicates) if there are fewer than 50 datapoints in total, or the smallest non-missing cell has <5 datapoints
- Chi square test if there are more than 50 datapoints in total, and non-missing cells all have more than five datapoints

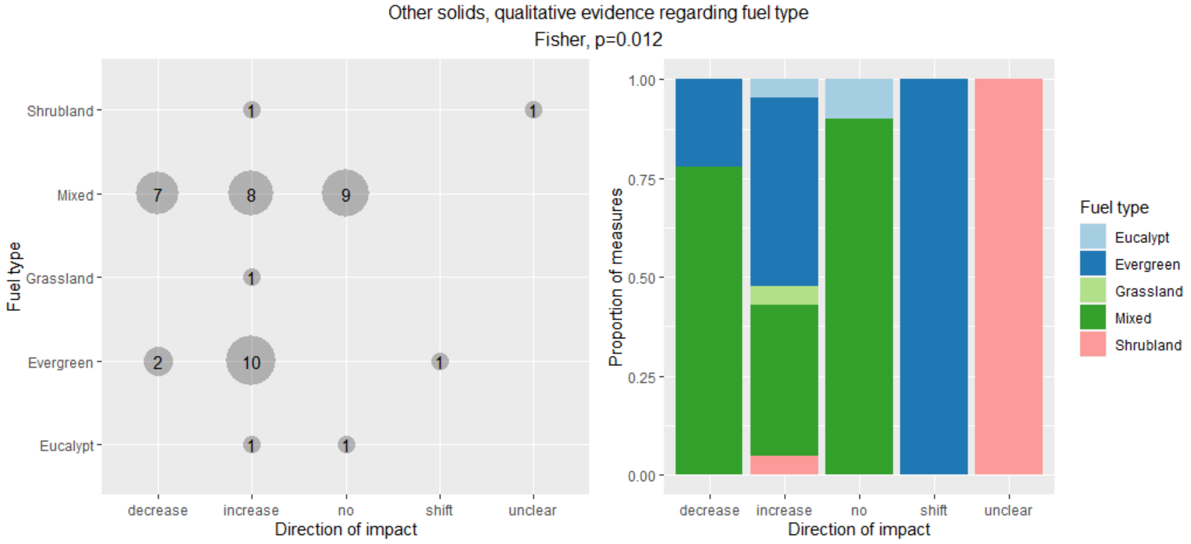
Statistical significance is set to α <0.05. It should be noted that these tests are undertaken on qualitative data summaries, and should be interpreted accordingly. The left panel depicts the total amount of available evidence, where the size of the circle scales to the number of measures falling within that particular category. The right panel depicts the proportion of fuel type by direction of evidence.

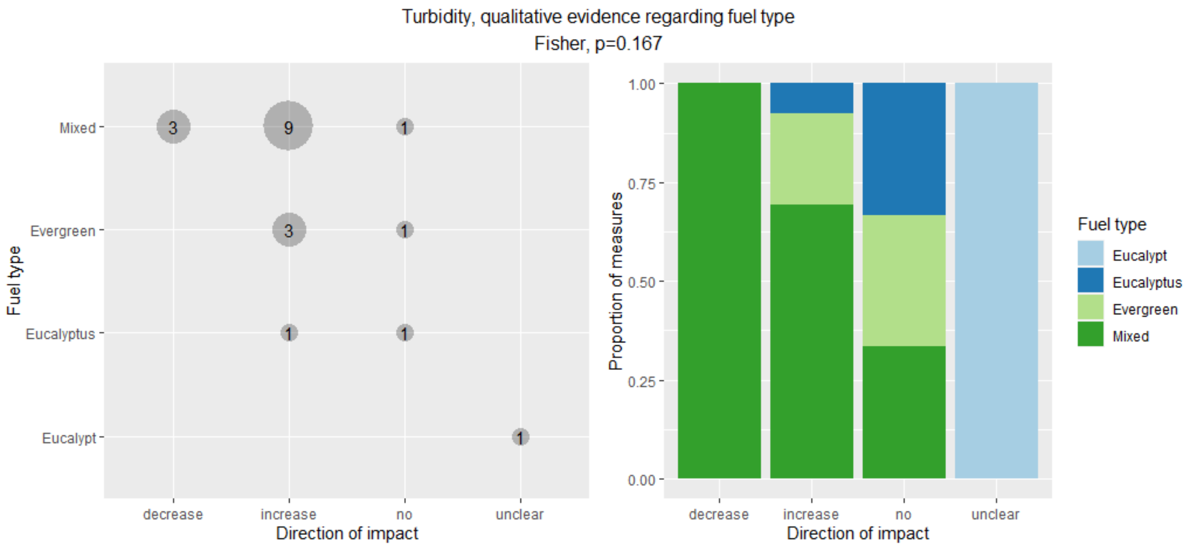
Physical Factors

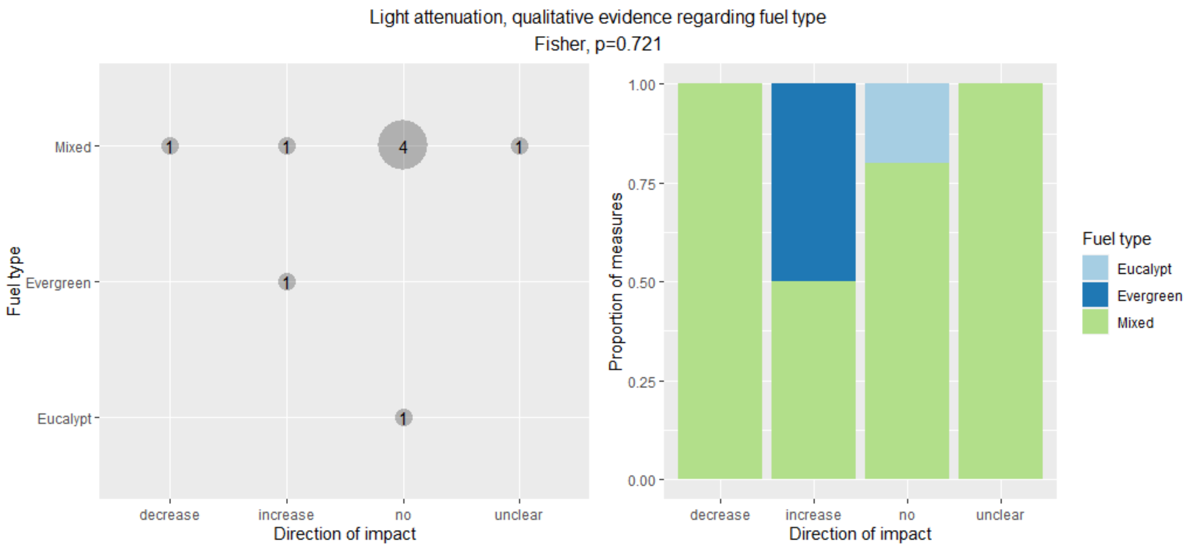


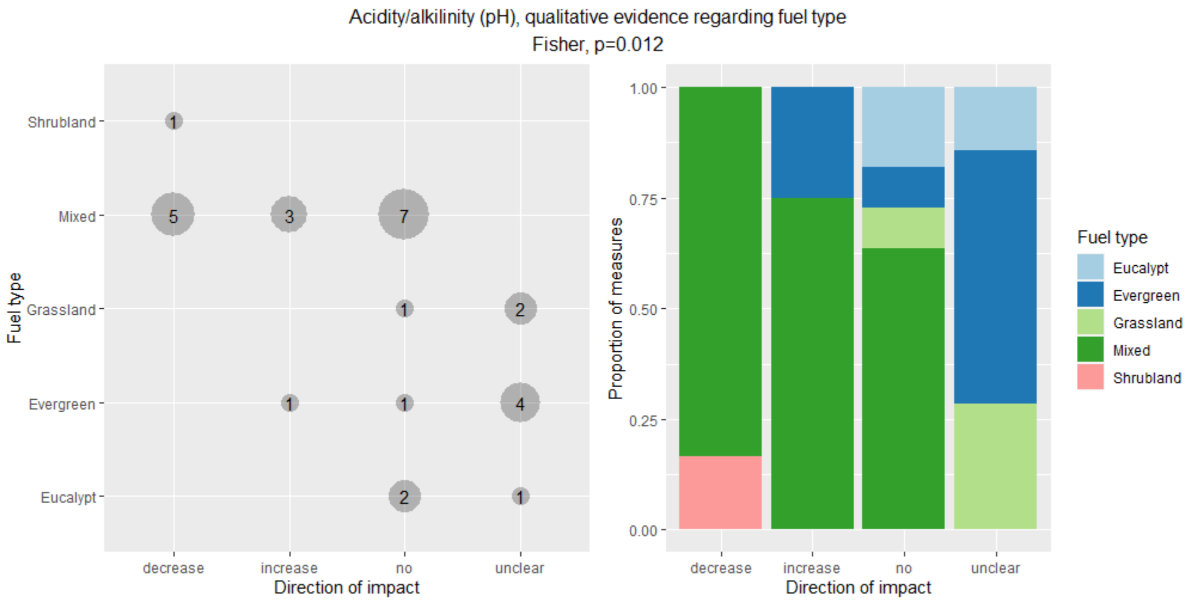

Sediment, qualitative evidence regarding fuel type
Fisher, p=0.493
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
Deciduous
3
2
13
1
1
1
3
1
3
2
11
3
1
2
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Grassland
Mixed
Shrubland

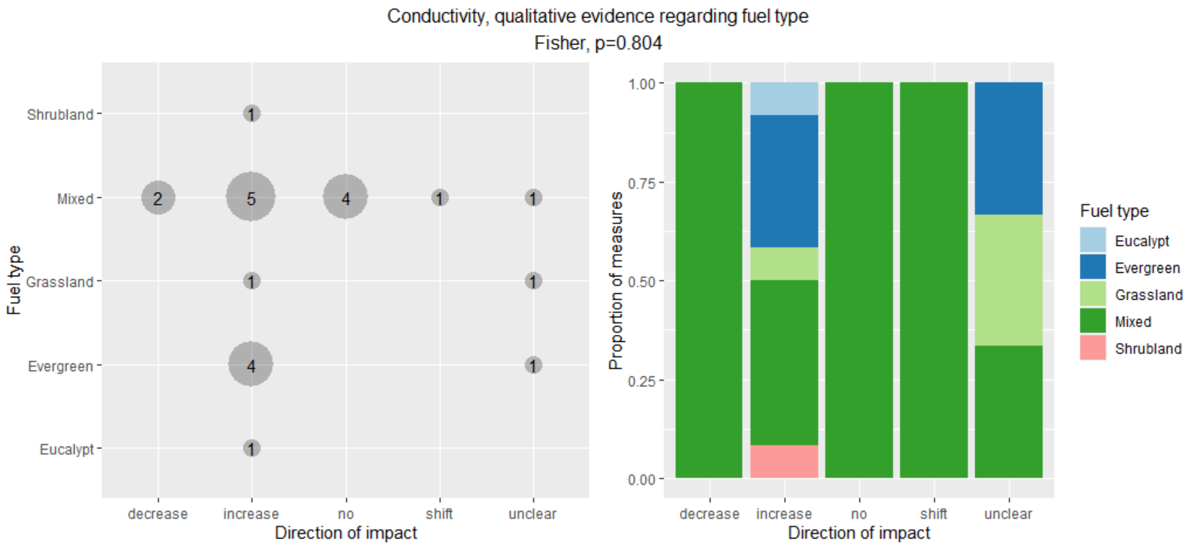

Particle size, qualitative evidence regarding fuel type
Fisher, p=0.083
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
1
11
3
2
2
1
2
3
1
4
1
1
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland

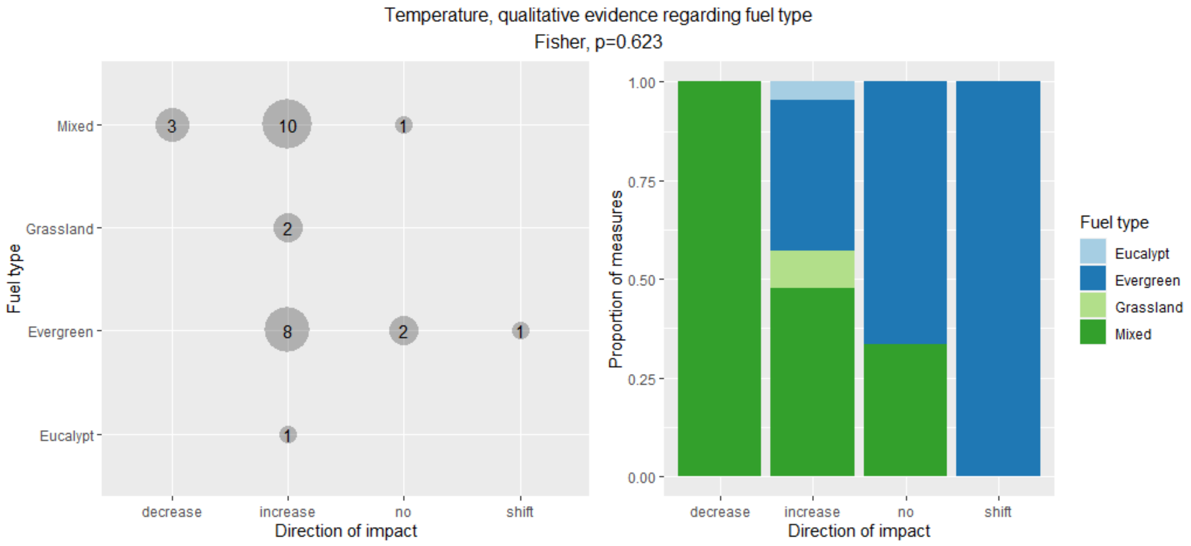

Other solids, qualitative evidence regarding fuel type
Fisher, p=0.012
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
1
1
7
8
9
1
2
10
1
1
1
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland


Turbidity, qualitative evidence regarding fuel type
Fisher, p=0.167
Fuel type
Mixed
Evergreen
Eucalyptus
Eucalypt
3
9
1
3
1
1
1
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Eucalyptus
Evergreen
Mixed

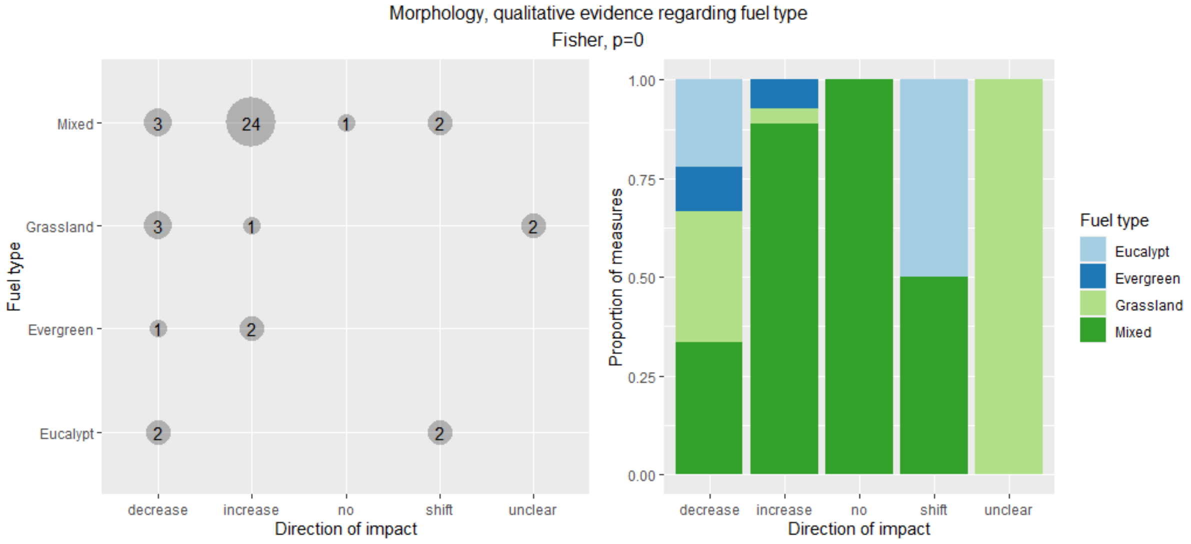

Light attenuation, qualitative evidence regarding fuel type
Fisher, p=0.721
Fuel type
Mixed
Evergreen
Eucalypt
1
1
4
1
1
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed


Acidity/alkilinity (pH), qualitative evidence regarding fuel type
Fisher, p=0.012
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
1
5
3
7
1
2
1
1
4
2
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland


Conductivity, qualitative evidence regarding fuel type
Fisher, p=0.804
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
2
5
4
1
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland

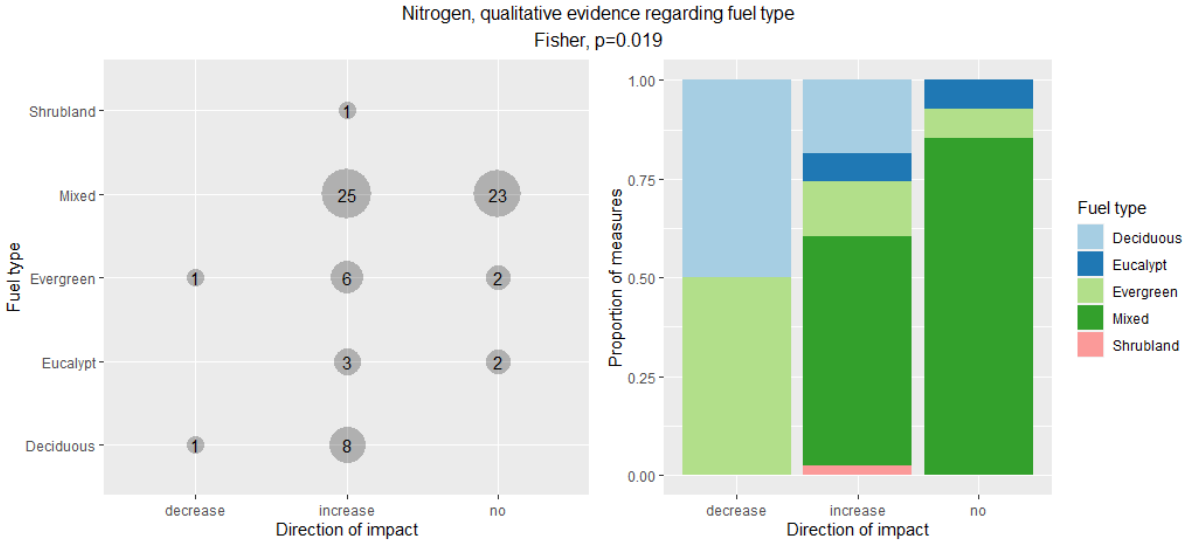

Temperature, qualitative evidence regarding fuel type
Fisher, p=0.623
Fuel type
Mixed
Grassland
Evergreen
Eucalypt
3
10
2
8
1
decrease
increase
no
shift
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
Fuel type
Eucalypt
Evergreen
Grassland
Mixed

Transport, qualitative evidence regarding fuel type
Fisher, p=0.032

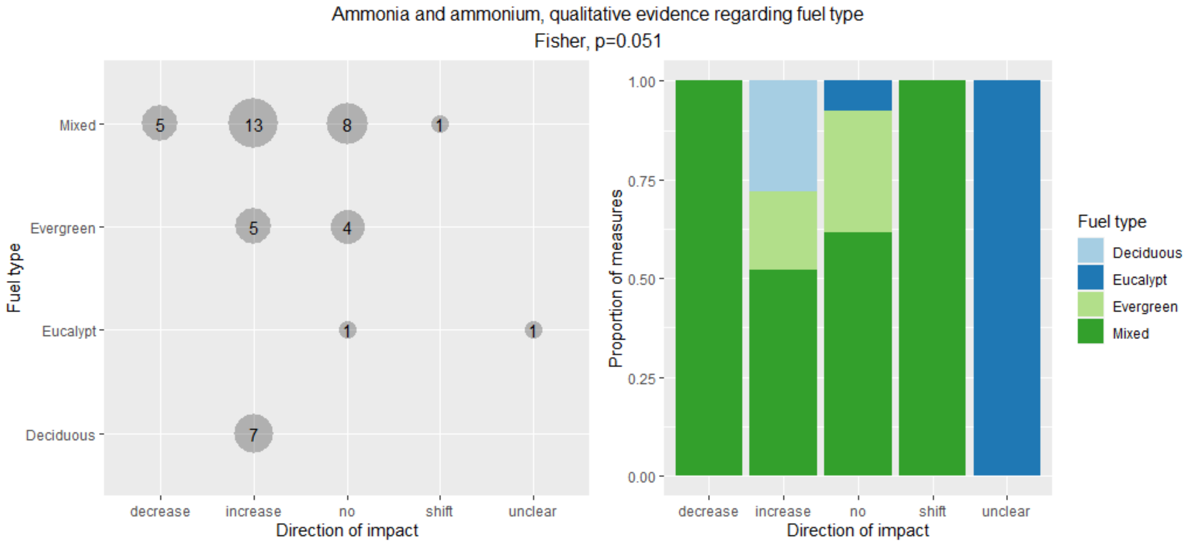


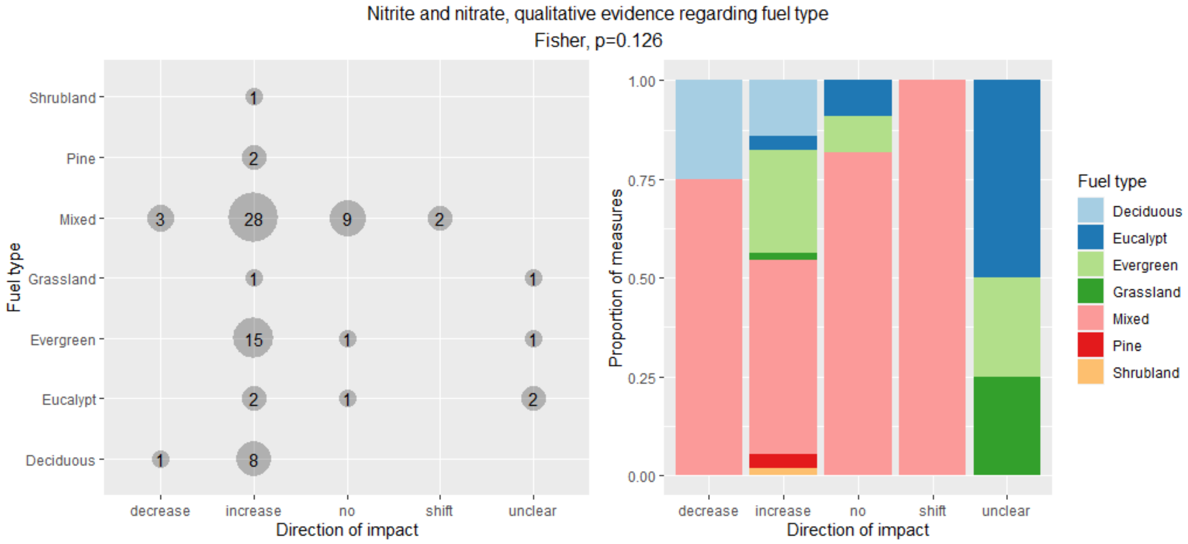
Morphology, qualitative evidence regarding fuel type
Fisher, p=0

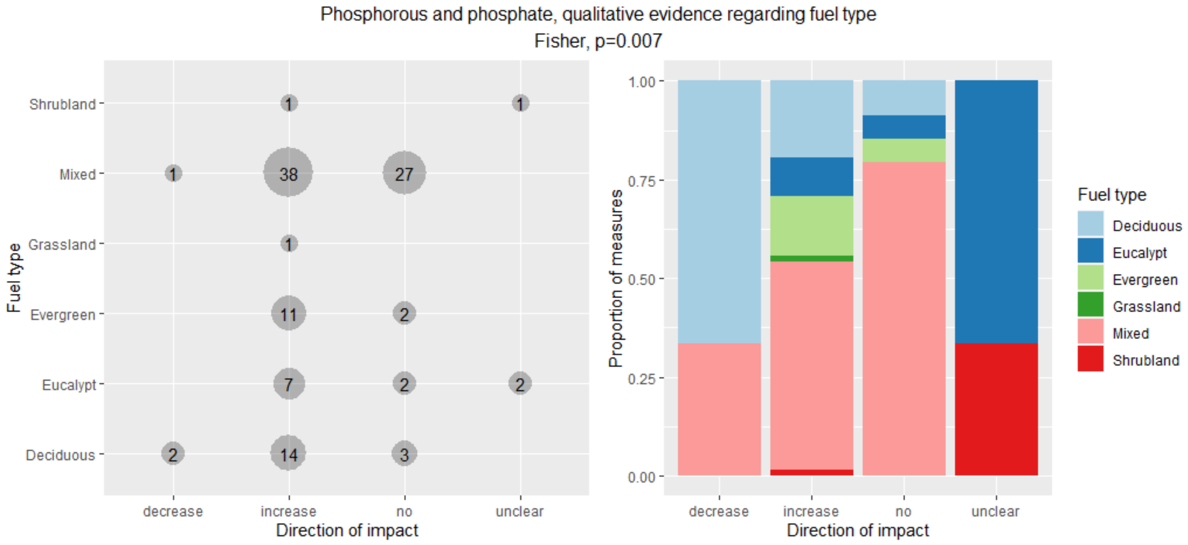
Chemical Factors

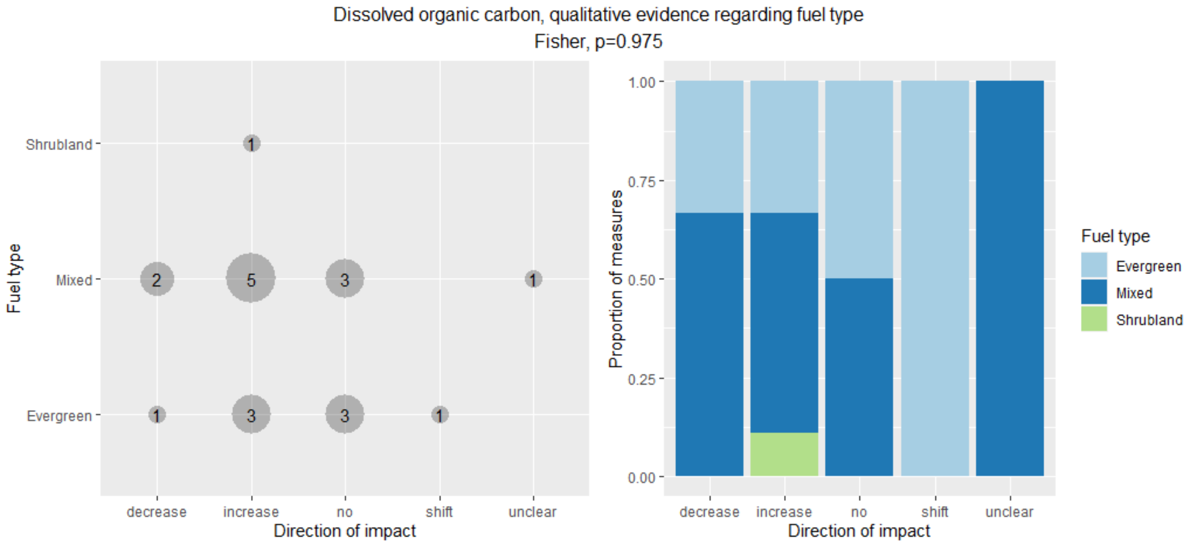


Nitrogen, qualitative evidence regarding fuel type
Fisher, p=0.019

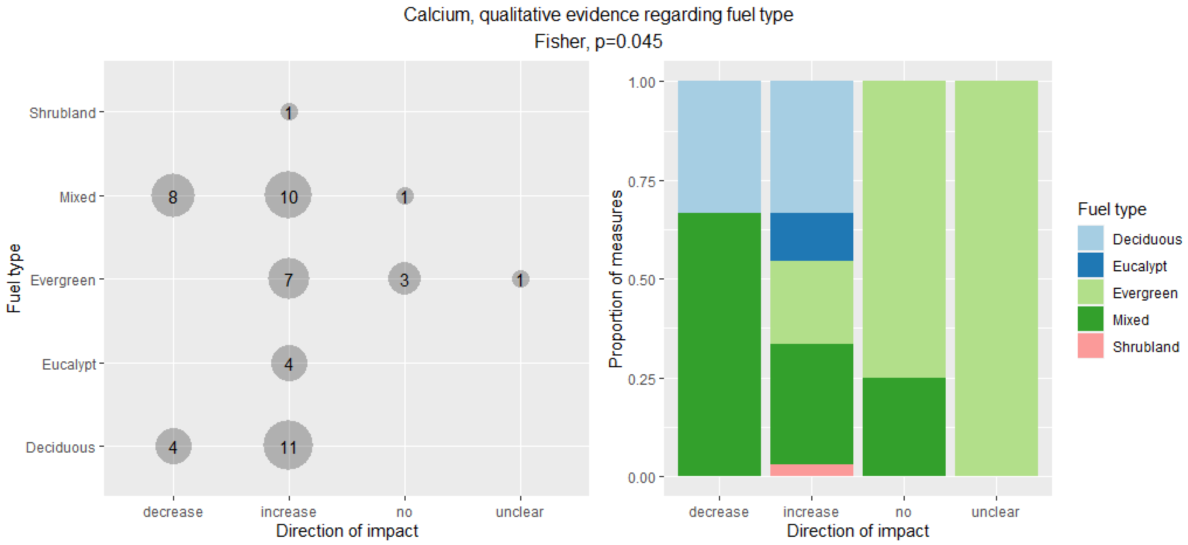

Ammonia and ammonium, qualitative evidence regarding fuel type
Fisher, p=0.051
Fuel type
Mixed
Evergreen
Eucalypt
Deciduous
5
13
8
1
5
4
1
1
7
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
0.00
0.25
0.50
0.75
1.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Mixed

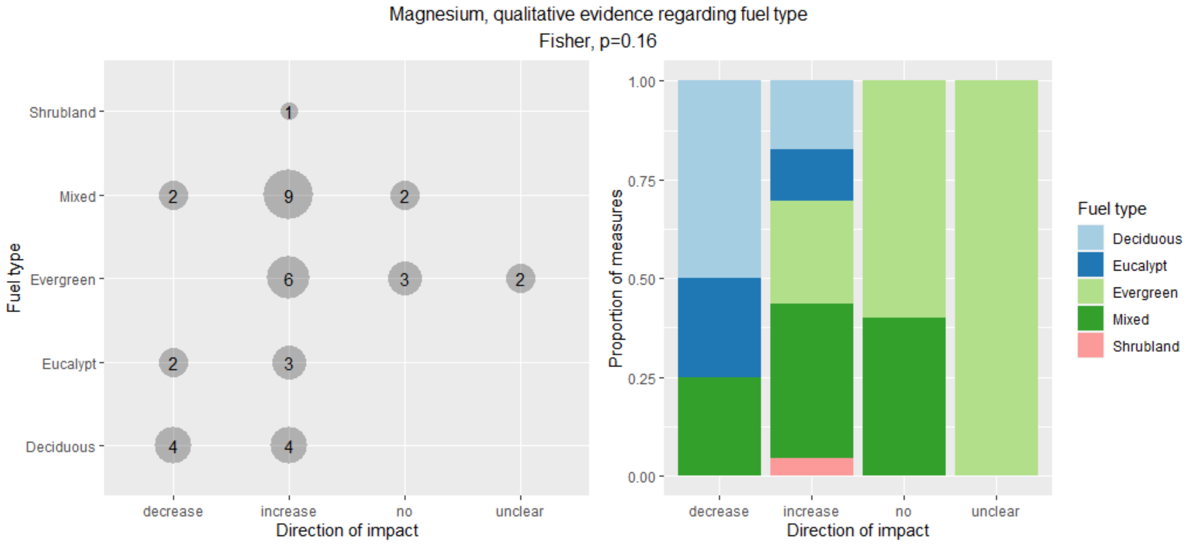

Nitrite and nitrate, qualitative evidence regarding fuel type
Fisher, p=0.126
Fuel type
Shrubland
Pine
Mixed
Grassland
Evergreen
Eucalypt
Deciduous
1
2
3
28
9
2
1
1
15
1
1
2
1
2
1
8
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
0.00
0.25
0.50
0.75
1.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Grassland
Mixed
Pine
Shrubland

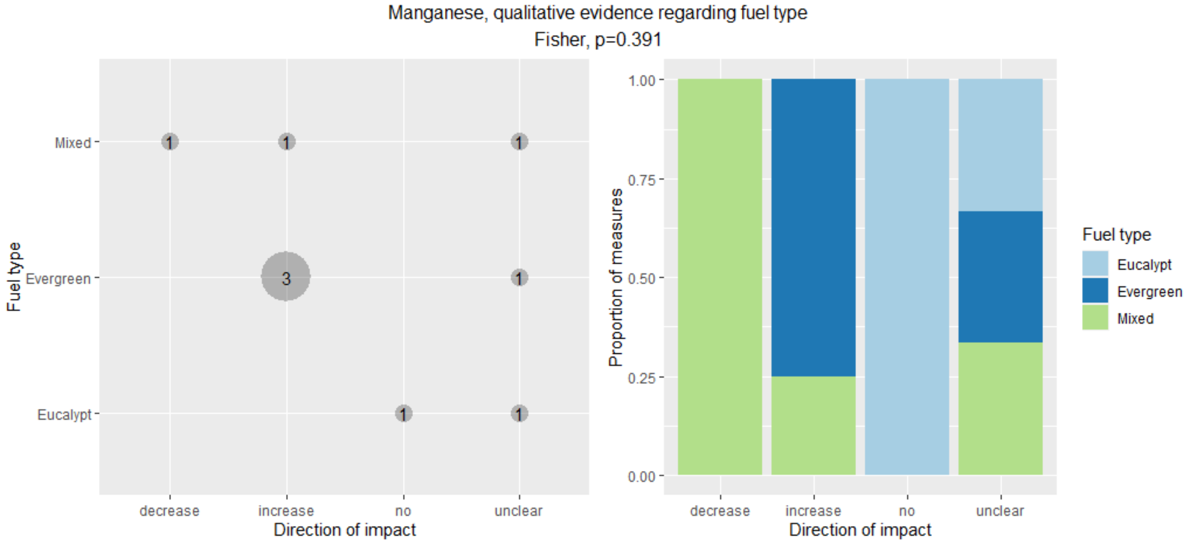


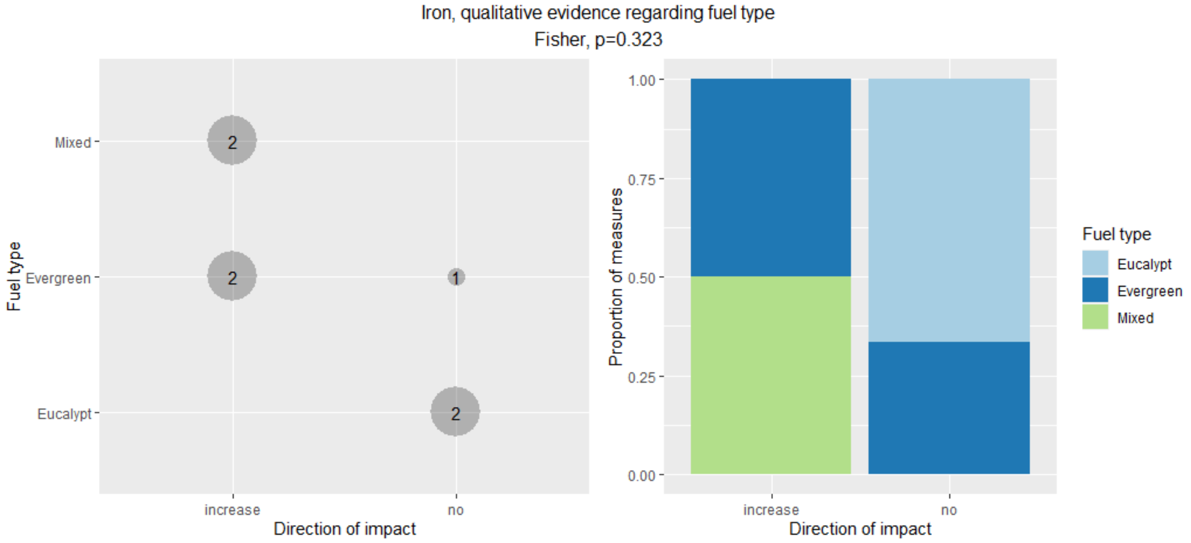


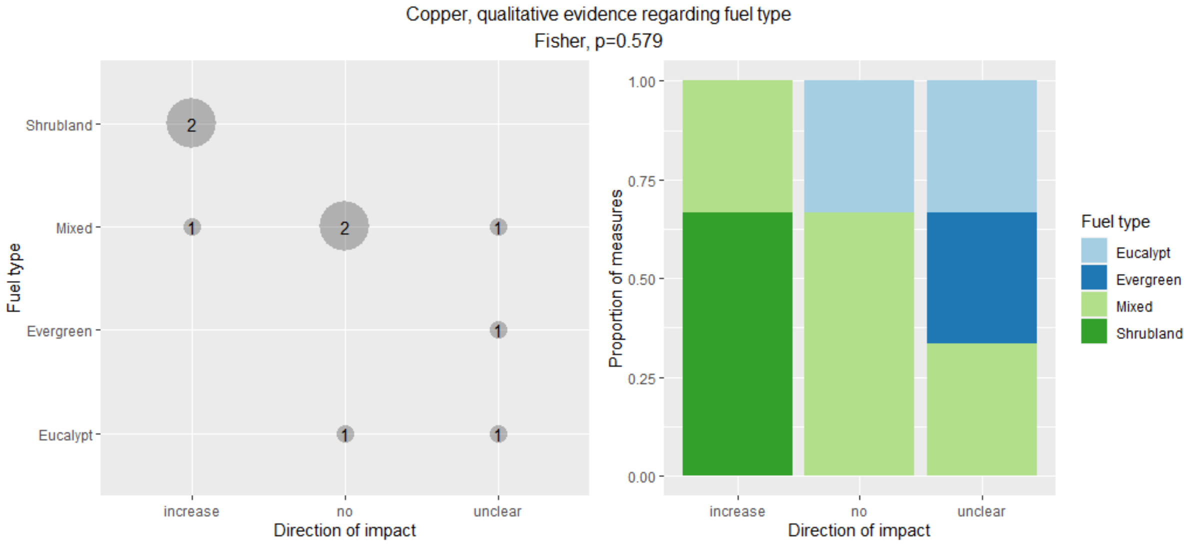
Biological Factors



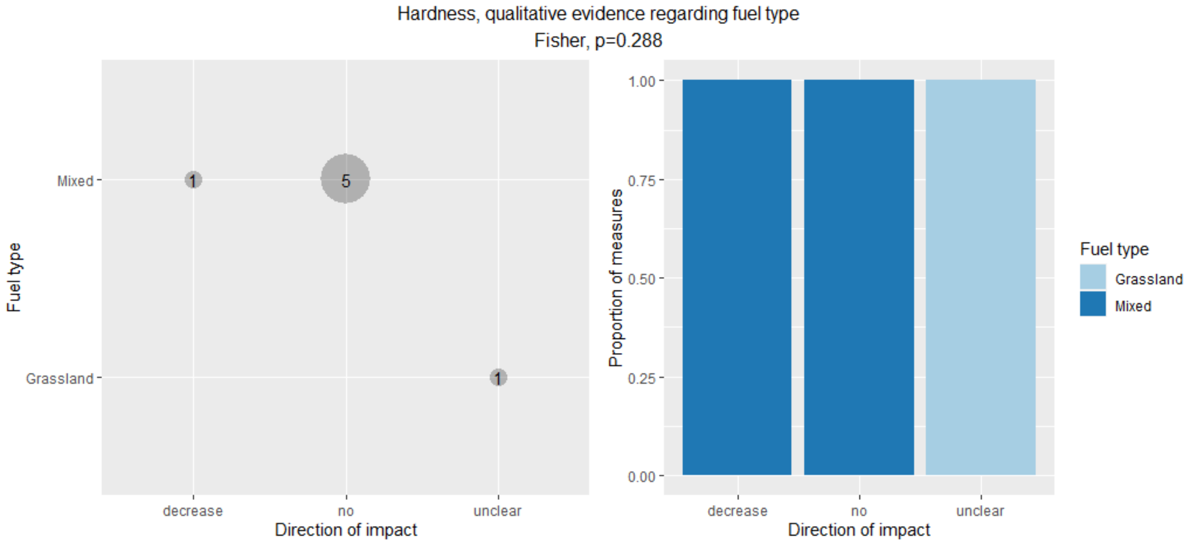

Magnesium, qualitative evidence regarding fuel type
Fisher, p=0.16
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
Deciduous
1
2
9
2
6
3
2
2
3
4
4
decrease
increase
no
unclear
Direction of impact
Proportion of measures
0.00
0.25
0.50
0.75
1.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Mixed
Shrubland

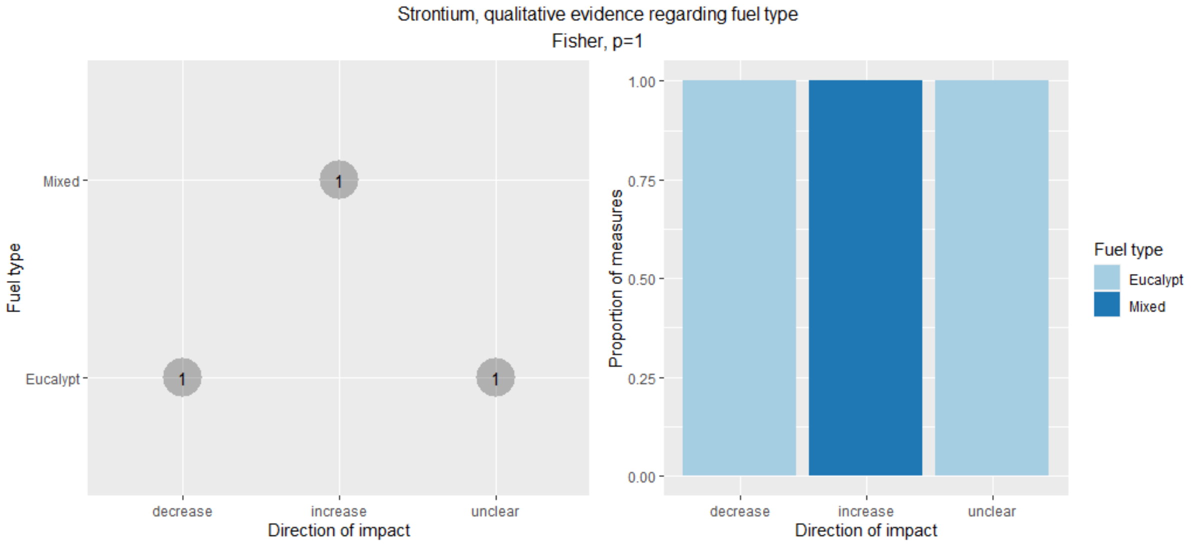

Manganese, qualitative evidence regarding fuel type
Fisher, p=0.391
Fuel type
Mixed
Evergreen
Eucalypt
1
1
1
3
1
1
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
0.00
0.25
0.50
0.75
1.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed

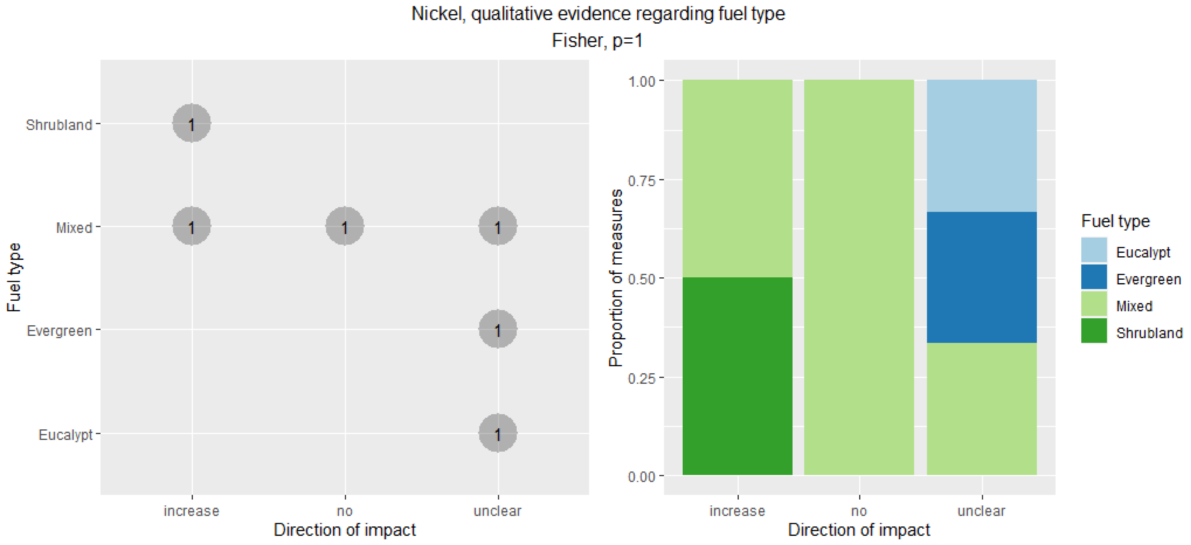

Iron, qualitative evidence regarding fuel type
Fisher, p=0.323
Fuel type
Mixed
Evergreen
Eucalypt
2
2
1
2
increase
no
Direction of impact
Proportion of measures
0.00
0.25
0.50
0.75
1.00
increase
no
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed

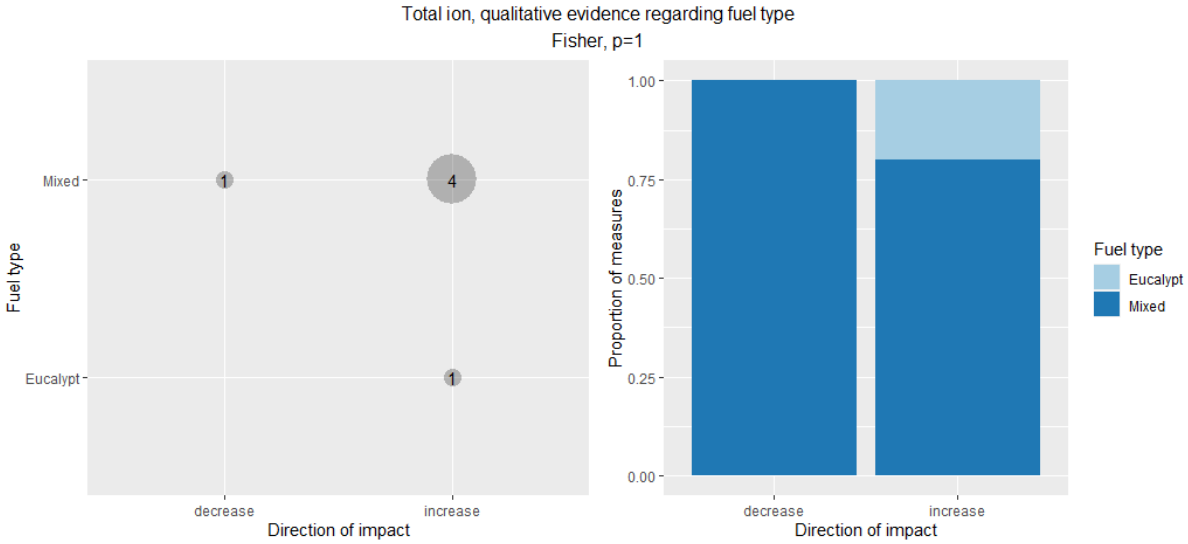

Copper, qualitative evidence regarding fuel type
Fisher, p=0.579
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
2
1
2
1
1
1
1
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed
Shrubland

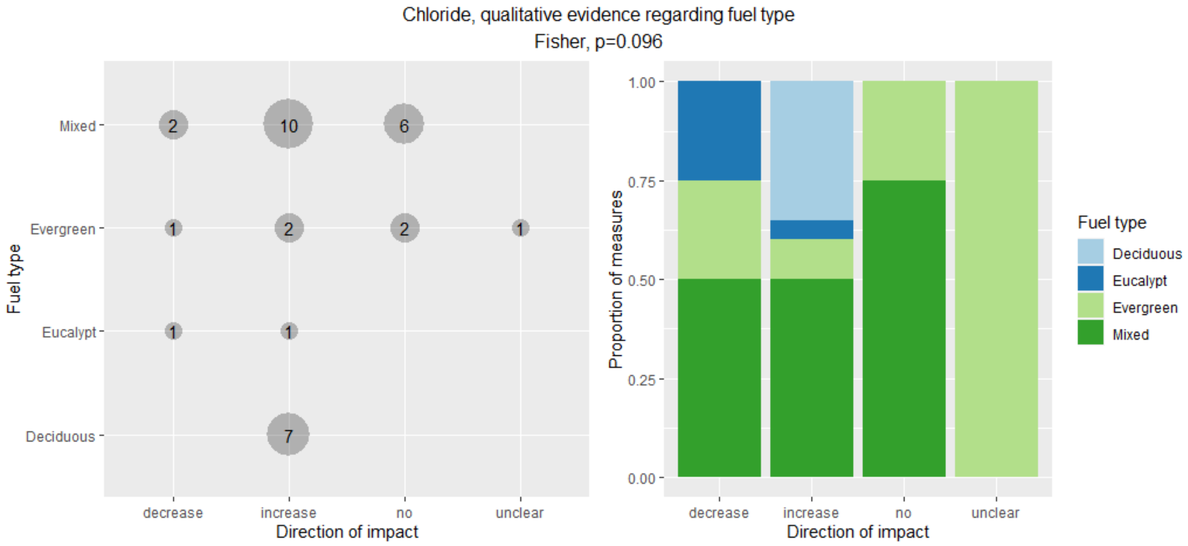

Zinc, qualitative evidence regarding fuel type
Fisher, p=0.315
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
2
2
1
1
1
decrease
increase
no
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed
Shrubland

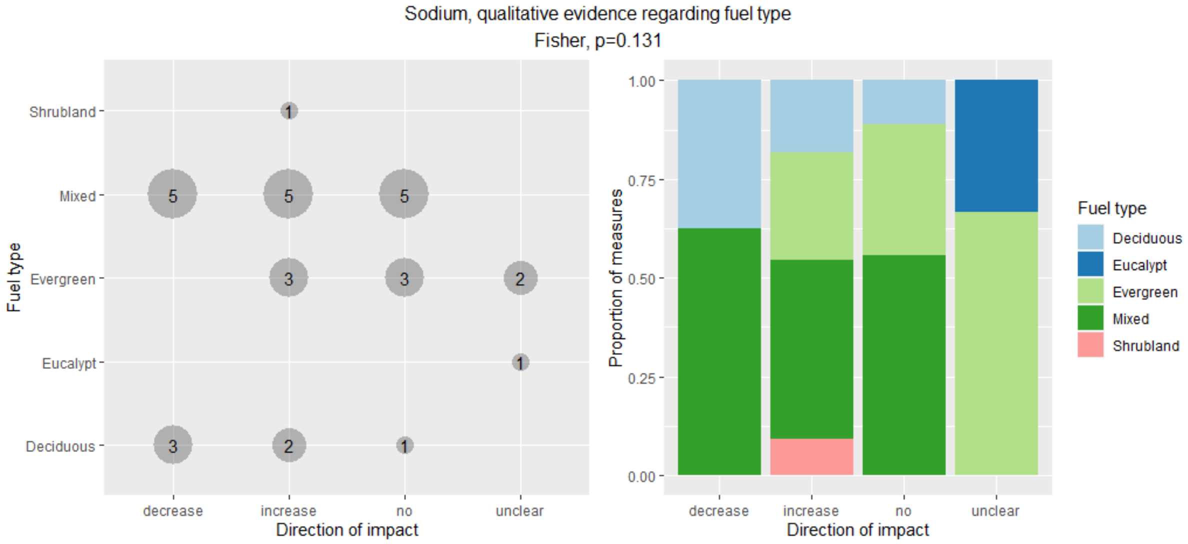

Hardness, qualitative evidence regarding fuel type
Fisher, p=0.288
Fuel type
Mixed
Grassland
1
5
1
decrease
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
no
unclear
Direction of impact
Fuel type
Grassland
Mixed

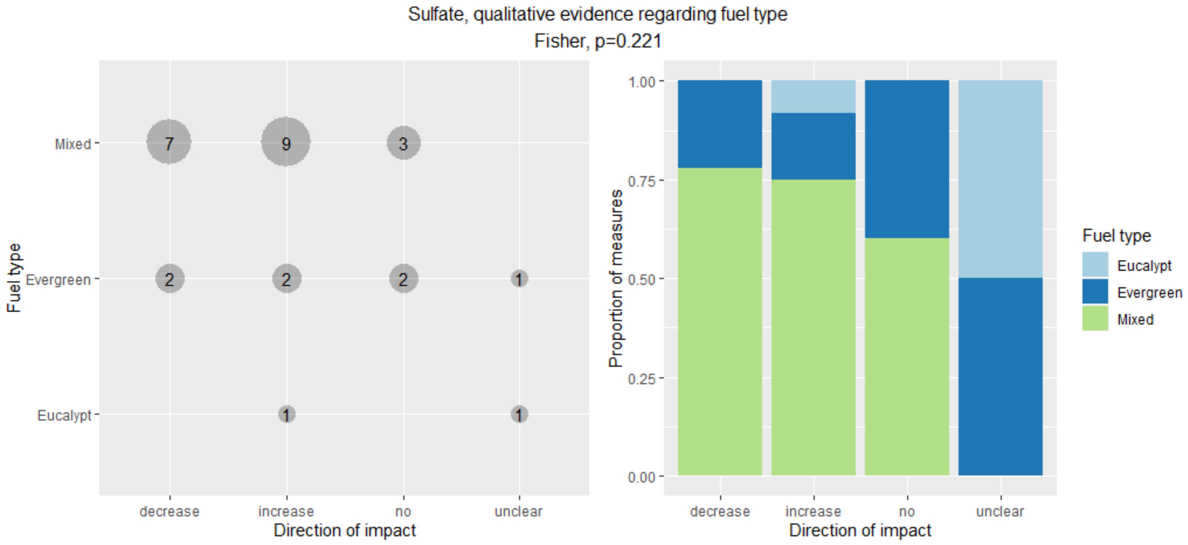

Strontium, qualitative evidence regarding fuel type
Fisher, p=1
Fuel type
Mixed
Eucalypt
1
1
1
decrease
increase
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
unclear
Direction of impact
Fuel type
Eucalypt
Mixed


Nickel, qualitative evidence regarding fuel type
Fisher, p=1
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
1
1
1
1
1
1
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed
Shrubland

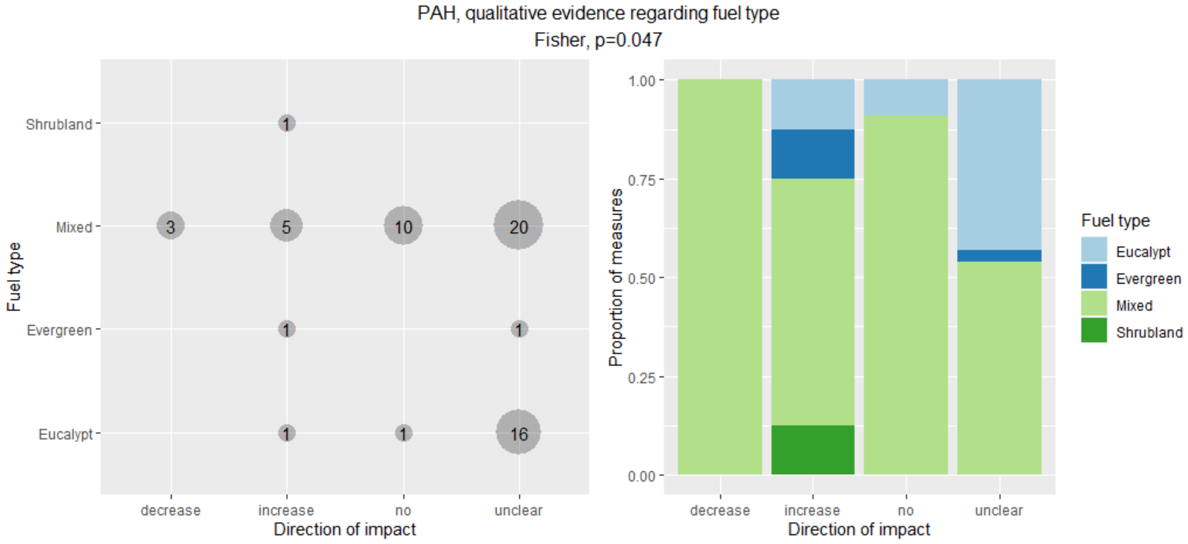

Total ion, qualitative evidence regarding fuel type
Fisher, p=1
Fuel type
Mixed
Eucalypt
1
4
1
decrease
increase
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
Direction of impact
Fuel type
Eucalypt
Mixed

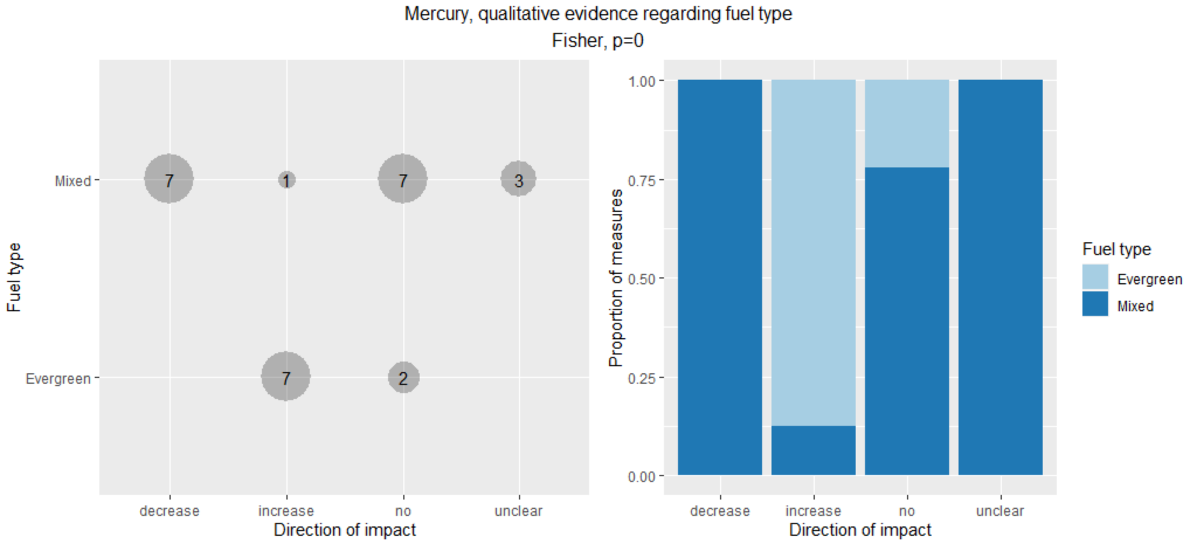

Chloride, qualitative evidence regarding fuel type
Fisher, p=0.096
Fuel type
Mixed
Evergreen
Eucalypt
Deciduous
2
10
6
1
2
2
1
1
1
7
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Mixed

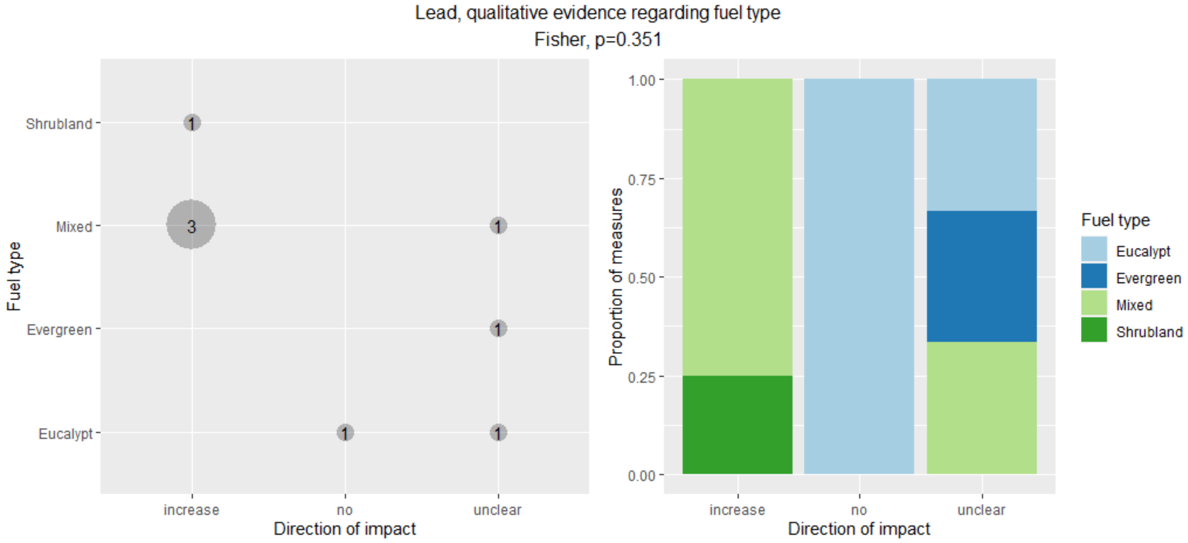

Sodium, qualitative evidence regarding fuel type
Fisher, p=0.131
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
Deciduous
1
5
5
5
3
3
2
1
3
2
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Mixed
Shrubland

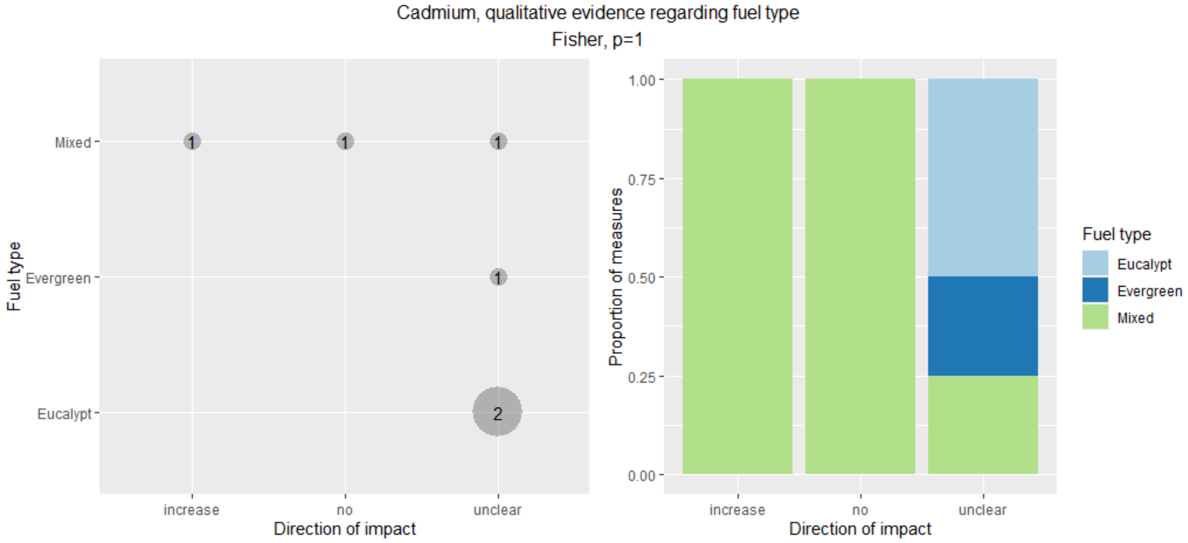

Sulfate, qualitative evidence regarding fuel type
Fisher, p=0.221
Fuel type
Mixed
Evergreen
Eucalypt
7
9
3
2
2
2
1
1
1
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed


Potassium, qualitative evidence regarding fuel type
Fisher, p=0.001
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
Deciduous
1
17
6
5
3
3
5
1
6
9
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Deciduous
Eucalypt
Evergreen
Mixed
Shrubland

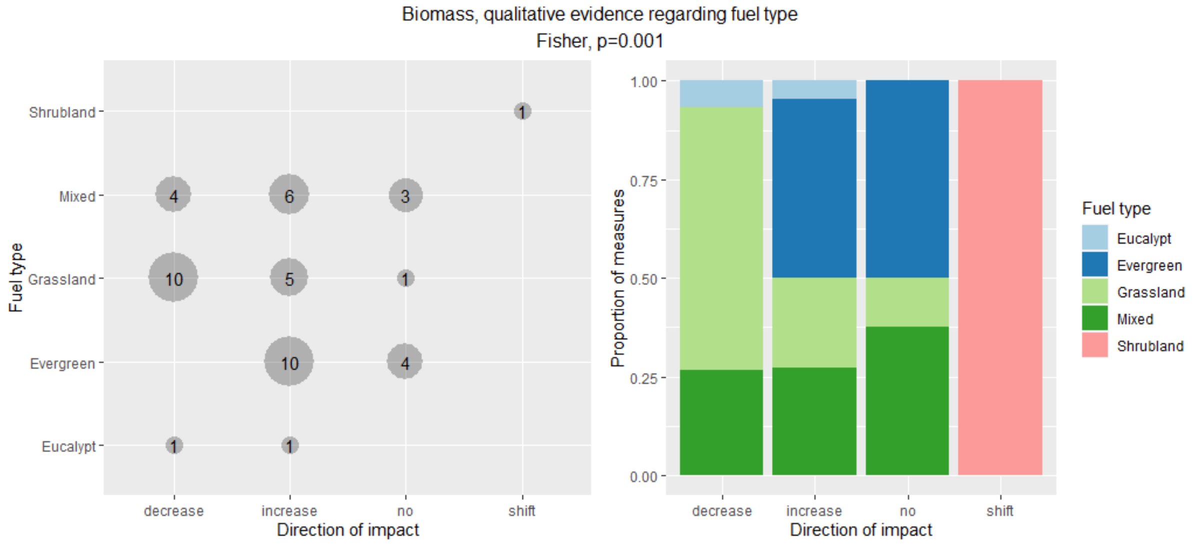

PAH, qualitative evidence regarding fuel type
Fisher, p=0.047
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
1
3
5
10
20
1
1
1
1
16
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Mixed
Shrubland

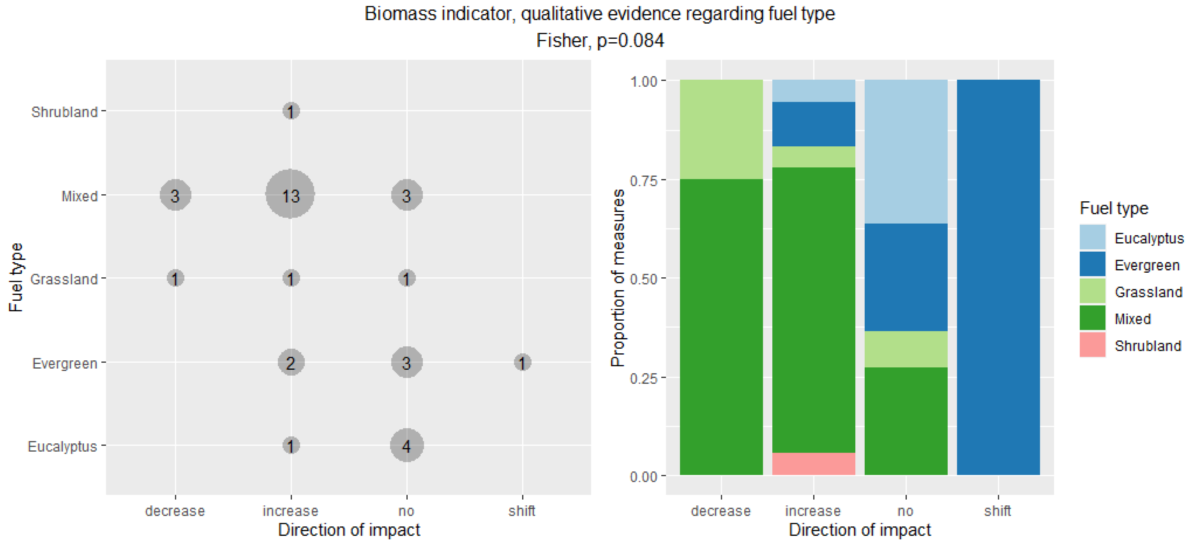

Mercury, qualitative evidence regarding fuel type
Fisher, p=0
Fuel type
Mixed
Evergreen
7
1
7
3
7
2
decrease
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
Fuel type
Evergreen
Mixed

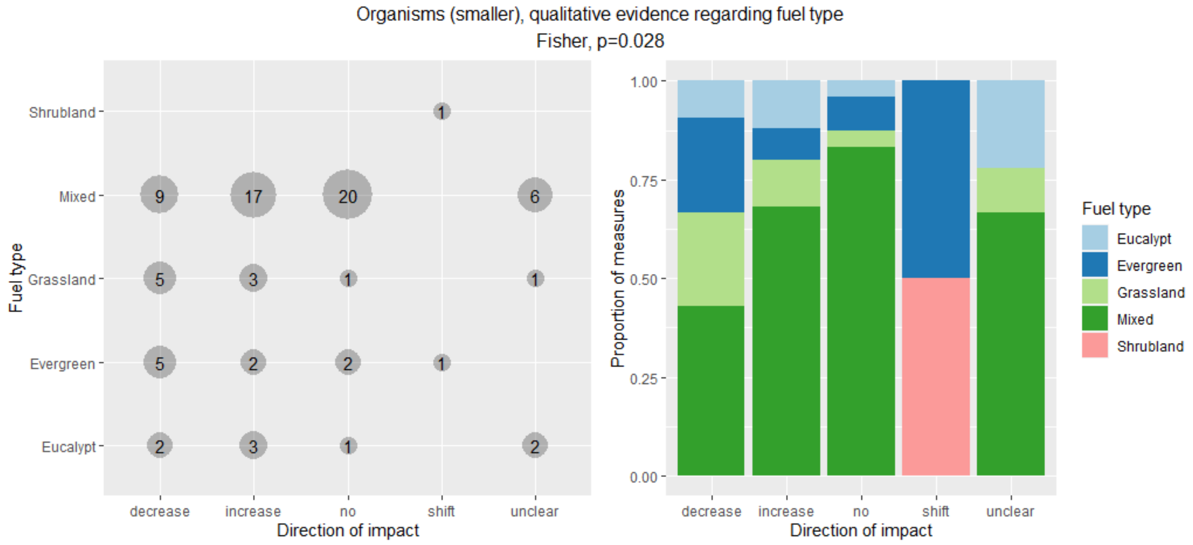

Lead, qualitative evidence regarding fuel type
Fisher, p=0.351
Fuel type
Shrubland
Mixed
Evergreen
Eucalypt
1
3
1
1
1
1
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
Fuel type
Eucalypt
Evergreen
Mixed
Shrubland

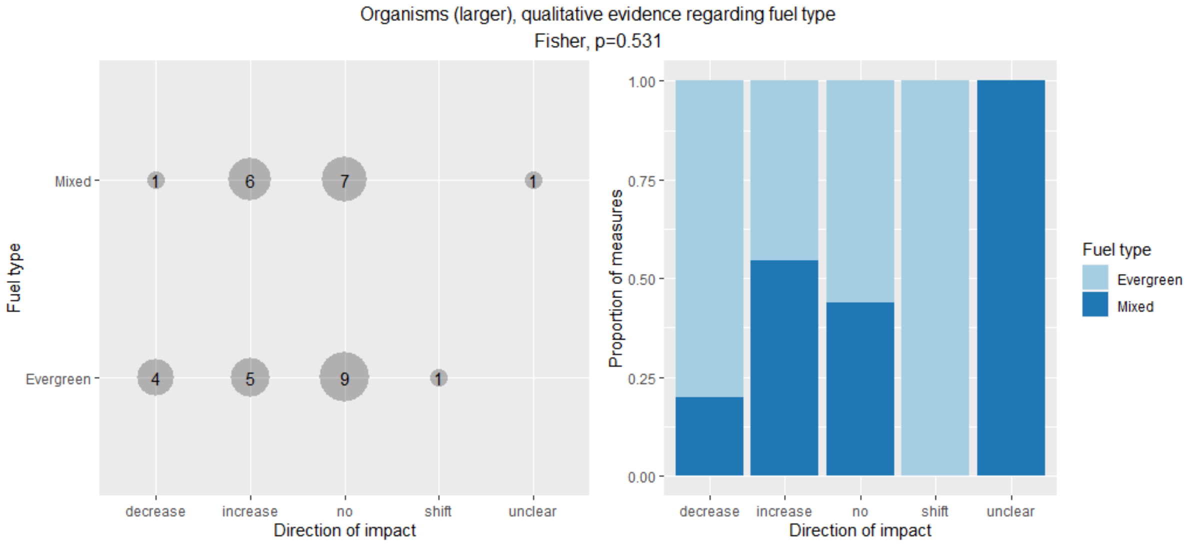

Cadmium, qualitative evidence regarding fuel type
Fisher, p=1
Fuel type
Mixed
Evergreen
Eucalypt
1
1
1
1
2
increase
no
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
Fuel type
Eucalypt
Evergreen
Mixed

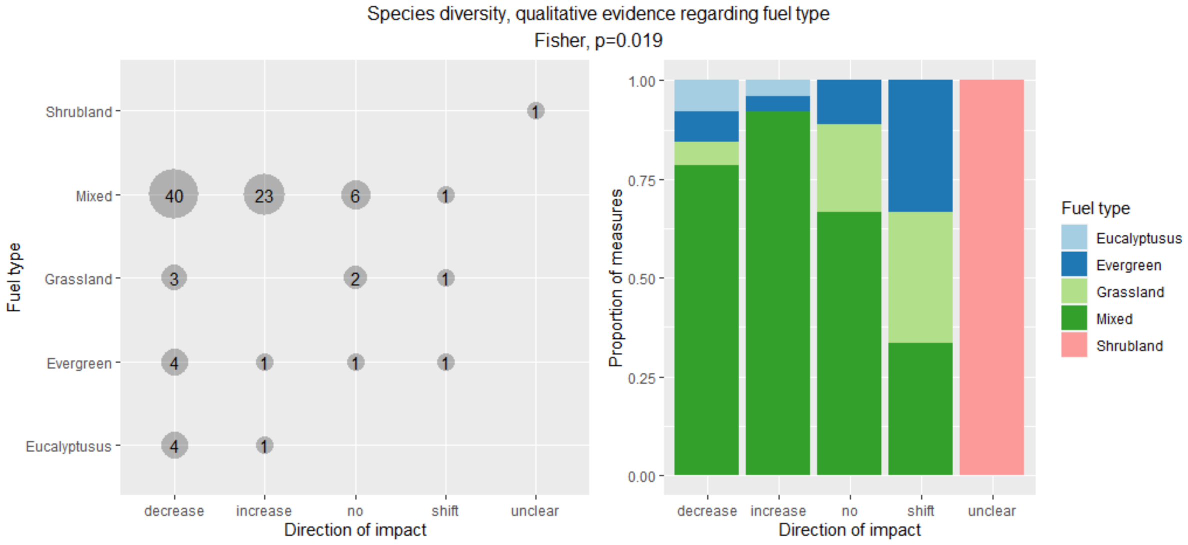
Biological


Biomass, qualitative evidence regarding fuel type
Fisher, p=0.001
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
1
4
6
3
10
5
1
10
4
1
1
decrease
increase
no
shift
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
Direction of impact
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland


Biomass indicator, qualitative evidence regarding fuel type
Fisher, p=0.084
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalyptus
1
3
13
3
1
1
1
2
3
1
1
4
decrease
increase
no
shift
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
Direction of impact
Fuel type
Eucalyptus
Evergreen
Grassland
Mixed
Shrubland


Organisms (smaller), qualitative evidence regarding fuel type
Fisher, p=0.028
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalypt
1
9
17
20
6
5
3
1
1
5
2
2
1
2
3
1
2
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Eucalypt
Evergreen
Grassland
Mixed
Shrubland


Organisms (larger), qualitative evidence regarding fuel type
Fisher, p=0.531
Fuel type
Mixed
Evergreen
1
6
7
1
4
5
9
1
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Evergreen
Mixed


Species diversity, qualitative evidence regarding fuel type
Fisher, p=0.019
Fuel type
Shrubland
Mixed
Grassland
Evergreen
Eucalyptusus
1
40
23
6
1
3
2
1
4
1
1
1
4
1
decrease
increase
no
shift
unclear
Direction of impact
Proportion of measures
1.00
0.75
0.50
0.25
0.00
decrease
increase
no
shift
unclear
Direction of impact
Fuel type
Eucalyptusus
Evergreen
Grassland
Mixed
Shrubland