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Measuring flammability of crops, pastures, fruit trees, and weeds: A novel tool to fight wildfires in agricultural landscapes

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HIGHLIGHTS

- Understanding the flammability of plant species is critical to managing fires on farms
- Fruit crops and cereals had higher flammability than vegetable crops, grazing herbs, pasture grasses, pasture legumes, and weeds
- Taxa with lower moisture content, higher dead materials and faster moisture loss rates were higher in flammability
- Redesigning agricultural landscape with low flammability species can be a useful tool to reduce fire hazards

GRAPHICAL ABSTRACT

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ABSTRACT

Fires on agricultural land account for 8–11 % of the total number of fires that occur globally. These fires burn through various crops, pastures, and native vegetation on farms, causing economic and environmental losses. Fire management on farms will be aided by understanding the flammability of plant species as this would allow the design of low-flammability agricultural landscapes, but flammability data on large numbers of agricultural species are lacking. Many crop and vegetable species are assumed to be low in flammability, but this has rarely been tested. Therefore, we examined the shoot and whole-plant flammability of 47 plant taxa commonly grown on farms in Canterbury, New Zealand, which included many globally common temperate agricultural crops. We demonstrated that most of the agricultural species were low to very low in flammability, with many of them (24 taxa; 51 %) not igniting in the experimental burning. Among different crop types, fruit crops and cereals had significantly higher flammability, while taxa categorized as vegetable crops, grazing herbs, pasture grasses, pasture legumes, and weeds were lower in flammability. We further showed that taxa with lower moisture content, higher retention of dead material and faster moisture loss rates were higher in flammability. The strong variation of flammability between the studied taxa suggests that the selection of suitable low flammability species and strategic redesign of agricultural landscapes with fire-retardant planting can be a useful tool to reduce fire hazards and impacts of wildfires in agricultural landscapes.

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1. Introduction

Wildfires are increasing in frequency and intensity due to global climate change, land-use change, and increasing human activities around forested areas, resulting in large-scale destruction socially, economically, and ecologically (Mann et al., 2016; Abram et al., 2021; UNEP, 2022). With the increase in extreme wildfire events globally, better protection of lives, properties, crops, livestock and natural heritage is needed, and different wildfire management approaches are being explored (Fernandes, 2013; Tedim et al., 2019; Moreira et al., 2020; Hessburg et al., 2021). While many studies have focused on wildfire incidence and their management in forest, savannah, and grassland ecosystems, fire occurrence and its consequences in agricultural landscapes are often overlooked.

Globally, 38 % of the land surface is utilized for livestock and crop production and with an increased human population, new land areas are being acquired for agriculture to fulfil the high food supply-demand in many countries (Friedl et al., 2002; Ramankutty et al., 2008). Agriculture fields have been identified as a major source of wildfire, mostly due to a higher number of fire ignitions recorded in various countries, particularly in Europe (Catry et al., 2009; Ganteaume et al., 2013a). Fire has been used as a vital farming tool for thousands of years and the lighting of fires in agriculture fields is a practice used to burn crop residues, control unexpected weeds, and reinvigorate soil health (Weinhold, 2011; Shyamsundar et al., 2019). However, these fires act as a potential ignition source for other, larger fires, and the presence of more human activities in the crop fields throughout the year to perform various agricultural activities, particularly the use of farm machinery, increases the risk of ignition (Leone et al., 2009; Martínez et al., 2009). Deliberate use or accidental occurrence of fire on farms is particularly concerning in the drier and warmer conditions predicted for many parts of the world due to climate change (Naumann et al., 2018; Arnell et al., 2019). Such fires can quickly get out of control, spreading rapidly into other vegetation, and nearby forests, and initiating large wildfires (Uhl and Kauffman, 1990; Aragão and Shimabukuro, 2010; Pearson et al., 2015). Fires on agricultural land account for 8–11 % of the total number of fires that occur globally (Korontzi et al., 2006) and threaten food security, economic growth, air quality, and public health as well as the surrounding ecosystems. Such fires burn through various crops, pastures, orchards, weeds, and other vegetation. Understanding the flammability of the constituent plant species will provide critical information to help explain fire behaviour in agricultural fields. Fire hazard management and wildfire preparedness are often focused on forested lands, shrublands and the wildland-urban interfaces, and the fire hazard in agricultural lands often gets overlooked.

Though higher ignitions are often recorded in agriculture fields (Catry et al., 2009; Ganteaume et al., 2013a), other studies have identified that cultivated areas such as croplands, and pastures are less fire-prone compared to shrubland and grassland, and coniferous forests (Nunes et al., 2005; Moreira et al., 2011; Oliveira et al., 2013). Agricultural activities have also been regarded as a key fire mitigation tool, especially in the wildland-urban interfaces where the cultivation of less flammable irrigated crops, pastures, and orchards have been found to stop or reduce the intensity of fire (Moreira et al., 2011; Oliveira et al., 2013). Studies in Mediterranean regions showed that expanding agricultural fields can minimize the negative impacts of wildfire on the surrounding ecosystems and society by reshaping fuel loads and connectivity, and facilitating firefighting operations (Loepfe et al., 2010; Aquilué et al., 2020). Diversifying agricultural crops and application of green firebreaks comprised of low flammability plant species are some of the emerging approaches that can be effective in changing fire regimes, while at the same time helping to conserve biodiversity in the Anthropocene (Moreira and Pe'er, 2018; Kelly et al., 2020).

To explore the potential of deploying low-flammability crops as a barrier to fire spread in agricultural landscapes, we first need to measure the flammability of a wide range of crops and other plant species found on farms. There has been an increasing number of flammability studies demonstrating that plant species vary in their flammability, but these studies have tended to focus on native or invasive species in natural areas or on the wildland-urban interface (Calitz et al., 2015; Wyse et al., 2016; Cui et al., 2020; Murray et al., 2023). While there has been extensive research undertaken to examine fire behaviour during crop fires (e.g., Cheney and Sullivan, 2008), there has been little comparison of the flammability of crop species. Among the field-based studies, Xaud et al. (2009) found that pineapples would be an effective crop-based green firebreak in Brazil when compared to peanuts and forage legumes. Also, Baxter and Woosaree (2013) showed that pasture species, such as Rocky Mountain fescue (*Festuca saximontana*), white clover (*Trifolium repens*), and yarrow (*Achillea millefolium*), were more likely to suppress fires than grasses such as fringed brome grass (*Bromus ciliatus*) and tufted hairgrass (*Deschampsia cespitosa*) in Canada. However, there have been no published studies comparing the flammability of a large number of species found in agricultural landscapes. Such data are crucial to identify the candidate low-flammability species upon which agricultural landscapes could be redesigned to reduce fire hazards.

To address this knowledge gap, we compared the flammability of 47 taxa found in Canterbury province, New Zealand that are commonly grown in agricultural fields as crops, pastures, legumes, and fruit trees, as well as several weeds commonly found growing in these agricultural fields. We also measured some fuel traits such as moisture content, percentage of dead materials and moisture loss rate to better understand their relationships with the flammability of the species. While this research was conducted in New Zealand, the findings will have wider application to redesign agricultural landscapes in other temperate zones, as many of the taxa sampled here are widely planted throughout the world. Overall, this study describes a process by which low flammability agricultural species can be identified and suggests some principles by which these species could be used to redesign agricultural landscapes to mitigate fire hazard.

2. Materials and methods

2.1. Study area

We conducted our study in Canterbury, New Zealand. The region accounts for 17 % of New Zealand's total land area and significantly contributes to agricultural output, consisting of about 20 % of its farmland (Dynes et al., 2010). The climate pattern of the Canterbury plain is characterized by dry westerly winds and low precipitation, with a mean annual rainfall of ~650 mm and a median annual temperature range of 10–13 °C (Macara, 2016; Mills and Moot, 2010). The soils are slightly to moderately acidic (pH 4.5–5.5) with low levels of N, P and S (Kemp et al., 1999). The dry weather of the region is intensified by a water deficit that often occurs between October and April, and the prevailing winds and decreased precipitation together increase the fire danger in this region during these months (Williams, 2009). Also, Canterbury has previously been ranked the highest in New Zealand for regional fire climate severity in a long-term fire climate study (Pearce and Clifford, 2008).

2.2. Sample collection

We collected samples from 47 taxa and grouped them into nine different crop types based on their societal use. These comprised four cereal crops, four forage crops, seven fruit trees, two grazing forbs, eight pasture grasses, four weeds, seven pasture legumes, five vegetables, and six wine grapes, across 18 families (Table 1). All taxa were found in the pastoral farms, wineries, and horticultural research areas managed by Lincoln University in or near Lincoln, Canterbury. The sampled taxa represent four trees, 13 grasses, three shrubs, 21 forbs, and six lianas, and include species that are commonly grown in agricultural landscapes globally. Following earlier studies (Jaureguiberry et al., 2011; Wyse

Table 1
Plant taxa included in this study. Taxonomy follows the New Zealand Plant Conservation Network (see: http://www.nzpcn.org.nz).

Species	Code	Family	Crop type	Growth form
Barley (*Hordeum vulgare* L.)	HORvul	Poaceae	Cereal crop	Grass
Oats (*Avena sativa* L.)	AVEfat	Poaceae	Cereal crop	Grass
Popcorn (*Zea mays var. everta*)	ZEAmay. Pop	Poaceae	Cereal crop	Grass
Wheat (*Triticum aestivum* L.)	TRIaes	Poaceae	Cereal crop	Grass
Fodder Beet (*Beta vulgaris* 'Mangelwurzel')	BETvul	Amaranthaceae	Forage crop	Forb
Kale (*Brassica oleracea* L. var. *Sabellica*)	BRAole	Brassicaceae	Forage crop	Forb
Sweet corn (*Zea mays* var. *rugosa*)	ZEAmay. Rug	Poaceae	Forage crop	Grass
Rapeseed (*Brassica napus* L.)	BRAnap	Brassicaceae	Forage crop	Forb
Braeburn Apple (*Malus domestica* 'Braeburn')	MALdom. Bra	Rosaceae	Fruit	Tree
Royal Gala Apple (*Malus domestica* 'Royal Gala')	MALdom. Roy	Rosaceae	Fruit	Tree
Olive (*Olea europaea* 'Barnea')	OLEeur	Oleaceae	Fruit	Tree
Blueberries (*Vaccinium* spp.)	VACspp	Ericaceae	Fruit	Shrub
Gooseberries (*Ribes uva-crispa* L.)	RIBuva	Grossulariaceae	Fruit	Shrub
Common Pear (*Pyrus communis* L.)	PYRcom	Rosaceae	Fruit	Tree
Raspberries (*Rubus idaeus* L.)	RUBida	Rosaceae	Fruit	Shrub
Chicory (*Cichorium intybus* L.)	CICint	Asteraceae	Grazing herb	Forb
Ribwort plantain (*Plantago lanceolata* L.)	PLAlan	Plantaginaceae	Grazing herb	Forb
Cocksfoot (*Dactylis glomerata* L.)	DACglo	Poaceae	Pasture grass	Grass
Italian Ryegrass (*Lolium multiflorum* Lam.)	LOLmul	Poaceae	Pasture grass	Grass
Pasture Brome (*Bromus valdivianus* Phil.)	BROval	Poaceae	Pasture grass	Grass
Perennial Ryegrass (*Lolium perenne* L.)	LOLper	Poaceae	Pasture grass	Grass
Bulbous canary-grass (*Phalaris aquatica* L.)	PHAaqu	Poaceae	Pasture grass	Grass
Prairie Grass (*Bromus willdenowii* Kunth.)	BROwil	Poaceae	Pasture grass	Grass
Tall Fescue (*Festuca arundinacea* Schreb.)	FESaru	Poaceae	Pasture grass	Grass
Timothy grass (*Phleum pratense* L.)	PHLpra	Poaceae	Pasture grass	Grass
Caucasian Clover (*Trifolium ambiguum* M.Bieb.)	TRIamb	Fabaceae	Pasture legume	Forb
Crown vetch (*Securigera varia* (L.) Lassen)	SECvar	Fabaceae	Pasture legume	Forb
Hairy canary-clover (*Lotus hirsutum* L.)	LOThir	Fabaceae	Pasture legume	Forb
Big trefoil (*Lotus pedunculatus* Cav.)	LOTped	Fabaceae	Pasture legume	Forb
Lucerne (*Medicago sativa* L.)	MEDsat	Fabaceae	Pasture legume	Forb
Red Clover (*Trifolium pratense* L.)	TRIpra	Fabaceae	Pasture legume	Forb
White Clover (*Trifolium repens* L.)	TRIrep	Fabaceae	Pasture legume	Forb
Bell Pepper (*Capsicum annuum* L.)	CAPann	Solanaceae	Vegetable	Forb
Dwarf Snow Pea (*Pisum sativum* L.)	PISsat	Fabaceae	Vegetable	Forb
Spring onion (*Allium fistulosum* L.)	ALLfis	Amaryllidaceae	Vegetable	Forb
Potatoes (*Solanum tuberosum* L.)	SOLtub	Solanaceae	Vegetable	Forb
Squash (*Cucurbita* spp. L.)	CUCspp	Cucurbitaceae	Vegetable	Forb
Common Mallow (*Malva neglecta* Wallr.)	MALneg	Malvaceae	Weed	Forb
Common Yarrow (*Achillea millefolium* L.)	ACHmil	Asteraceae	Weed	Forb
Broad-leaved dock (*Rumex obtusifolius* L.)	RUMobt	Polygonaceae	Weed	Forb
Fathen (*Chenopodium album* L.)	CHEalb	Amaranthaceae	Weed	Forb
Chardonnay (*Vitis vinifera* 'Chardonnay')	VITvin. Cha	Vitaceae	Winegrape	Liana
Merlot (*Vitis vinifera* 'Merlot')	VITvin. Mer	Vitaceae	Winegrape	Liana
Pinot Gris (*Vitis vinifera* 'Pinot Gris')	VITvin. Gri	Vitaceae	Winegrape	Liana
Pinot Noir (*Vitis vinifera* 'Pinot Noir')	VITvin. Noi	Vitaceae	Winegrape	Liana
Riesling (*Vitis vinifera* 'Riesling')	VITvin. Rei	Vitaceae	Winegrape	Liana
Sauvignon Blanc (*Vitis vinifera* 'Sauvignon Blanc')	VITvin. Sau	Vitaceae	Winegrape	Liana

et al., 2016), we collected 70 cm-long fresh, sun-exposed terminal branches for trees, shrubs, and lianas, and whole plants (all above-ground biomass) for the taxa <70 cm in height. For herbaceous individuals taller than 70 cm in height, we took a 70 cm sample of the main stem that represented those parts of the whole plant with most fuel. We sampled eight individual plants for each taxon, representing a total of 376 samples. Samples were collected and tested in March and April 2021 (late summer–early autumn), which are months at the end of the fire season in New Zealand (Pearce and Clifford, 2008). All samples were stored in sealed plastic bags at 4–8 °C to prevent moisture loss prior to flammability testing.

2.3. Flammability measurements

We conducted the burning experiments by following the methods and instruments used by Jaureguiberry et al. (2011) and further modified by Wyse et al. (2016). This method is considered a standard way of studying plant flammability (Perez-Harguindeguy et al., 2013; Alam et al., 2020) and similar protocols and instrumentation, with minor modifications, are being used in several countries to study the flammability of different plant species (Calitz et al., 2015; Santacruz-García et al., 2019; Cui et al., 2020; Zanzarini et al., 2022; Potts et al., 2022). All samples were air-dried for 24 h in a lab at room temperature (ca. 20 °C) before burning them, as per standard protocols (White and Zipperer, 2010; Wyse et al., 2018). Each sample was weighed, and its length, height, and width were measured after placing it on the burning device, to calculate fuel volume and bulk density. Also, the percentage of dead material retained on the sample was estimated visually by two observers.

The testing protocol followed that of Jaureguiberry et al. (2011) and Wyse et al. (2016), but is summarised here. First, the burner was turned on to heat up the grill and it was left on for the duration of the testing. Grill temperature was recorded before each sample measurement and the temperature was in the range 125–199 °C during the testing. Analysis showed that an increase in grill temperature did not increase sample flammability (see Fig. A.1 and the text therein). Samples were placed horizontally on the grill and preheated at the grill temperature for 2 min, following standard protocols (Jaureguiberry et al., 2011). The blowtorch was then turned on for 10 s to ignite the sample for each burning, with most flammability variables measured after the blow torch was turned off. We recorded four flammability variables: time to ignition (ignitibility) was recorded as the amount of time taken for the sample to ignite and measured in seconds; the maximum temperature reached (combustibility) was recorded as the highest temperature measured during burning by an infrared laser thermometer (Fluke 572; Fluke Corp., Everett, WA, USA); burning time (sustainability) was recorded as the time that the sample supported flaming combustion and was measured in seconds; and burnt biomass (consumability) was the percentage of the sample biomass consumed during burning and was estimated visually by two observers. Any sample that did not ignite once the blow torch was turned off was considered a non-ignition, and burning time and burnt biomass were recorded as zero, while the maximum temperature was recorded as 150 °C, as per Padullés Cubino et al. (2018). Time to ignition ranged between 0.5 and 9.5 s, which was rescaled by subtracting it from 10 to derive an ignition score by giving higher values to those species that ignited faster and lower values to those species that took the longest to ignite; e.g., a sample that ignited after 1 s had an ignition score of 9. Samples that did not ignite were given an ignition score of zero (Padullés Cubino et al., 2018).

Prior to air-drying the samples, a subsample of around 10 cm in length was taken from each sample and weighed to obtain the fresh mass (FM). These subsamples were re-measured during the day of burning (day of burning mass - BM) after air-drying for 24 h at room temperature with the samples and were then placed into dry ovens (at 65 °C) for 48 h to obtain the dry mass (DM). The moisture loss rate (MLR) per hour and moisture content (MC) of the sample on a dry mass basis of the subsamples at the time of burning was calculated following the Eqs. (1) & (2).

$$MLR = (\mathrm{FM} - \mathrm{BM})/\mathrm{T} \tag{1}$$

$$MC = [(\mathrm{FM} - \mathrm{DM})/\mathrm{DM}] \times 100 \tag{2}$$

2.4. Statistical analysis

We performed principal component analysis (PCA) to explore the variation and patterns of flammability across the species. First, we conducted a PCA using the flammability traits ignition score, maximum temperature, burn time, and burnt biomass at the taxon level ($n = 47$), where mean values from the different individuals of the same taxon were used. We found that the first axis of the PCA explained >90 % variation of the data and all the flammability traits were positively correlated, so we used the taxon scores on this axis to provide an index of flammability for the species tested and further exploratory analysis (see below). Taxa with the highest scores on the first axis had the highest values for the four flammability traits and therefore the highest overall flammability. This flammability index was further used to categorise the studied taxa into seven flammability levels, modified from Wyse et al. (2016): Very High, High, Moderate/High, Moderate, Low/Moderate, Low, and Very Low. We used K-means clustering for the flammability categorisation (Hartigan and Wong, 1979). In a second PCA, we explored the association between fuel traits (fuel bulk density, fuel moisture content, fuel dead materials, and moisture loss rate) and the four flammability variables for every sample of the tested species. We also constructed a correlation matrix using flammability variables, fuel traits, and PCA axes scores from the first PCA to further evaluate whether PCA axes and the flammability variables were associated with the fuel traits at the sample level of the tested taxa. We further explored the flammability variation of the taxa between the crop types using analysis of variance (ANOVA) on the first PCA axis flammability scores. ANOVAs were also performed to explore the variation of the fuel traits of the taxa between crop types followed by Tukey's post-hoc analysis. All statistical analyses were conducted using R version 4.1.3 (R Core Team, 2022). As all the variables were on different scales, we implemented the PCAs on centred and standardised data using the "PCA" function from the "FactoMiner" package (Lê et al., 2008) and visualized the outcomes using "factoextra" package (Kassambara and Mundt, 2020). The correlation matrix was plotted using "GGally" (Schloerke et al., 2021) and "tidyverse" (Wickham et al., 2019) packages. Tukey's post-hoc analysis was performed using "HSD.test" function from the "agricolae" package (De Mendiburu, 2014).

3. Results

3.1. Variation in flammability and fuel traits between taxa and crop types

The 47 taxa we tested showed wide variation in their flammability (Fig. 1). The first axis of the PCA conducted with the flammability variables explained 93.3 % variation of the data in the flammability of species and was positively associated with all four flammability traits: ignition score (loading = 0.49), maximum temperature (loading = 0.50), burn time (loading = 0.49) and burnt biomass (loading = 0.51). The second axis (PC2) explained 3.2 % variation in flammability and was positively associated with burn time (loading = 0.81) and negatively associated with ignition score (loading = −0.55), while the maximum temperature (loading = −0.15) and burnt biomass (loading = −0.09) showed a weak negative association. Taxa from the fruits category were the highest in flammability whereas taxa from grazing herbs, vegetables, weeds, and pasture grasses were the lowest in flammability (Fig. 1).

Flammability ranking of the tested taxa by their loading on PC1 showed that the most flammable taxon was common pear (*Pyrus communis*) in the Very High category, two apple varieties (*Malus domestica* var. Braeburn & *M. domestica* var. Granny smith) in the High category, followed by wheat (*Triticum aestivum*), raspberry (*Rubus idaeus*) and oats (*Avena sativa*) in Moderate-High category (Fig. 2). All these taxa had faster ignition, higher maximum temperatures reached, longer burn times, and more biomass consumed than other taxa. Taxa in the Low Flammability category included hairy canary (*Securigera varia*), squash (*Cucurbita* spp.), gooseberries (*Ribes uva-crispa*), three wine grape varieties (*Vitis vinifera* – Merlot, Sauvignon Blanc and, Chardonnay) and fathen (*Chenopodium album*). A large number of taxa tested (28; 60 %) were in the Very Low category, and most of them (24; 51 %) were so low that no samples of those taxa ignited in the burning tests (Fig. 2). The exception to this in the Very Low category were red clover (*Trifolium pratense*), reisling grapes (*Vitis vinifera*), phalaris (*Phalaris aquatica*) and plantain (*Plantago lanceolata*), which had no ignitions for most of their samples.

Analysis of variance showed that flammability variables and fuel traits of the taxa varied significantly between different crop types (Figs. 3, A.2). Taxa from the fruits and cereal crops had significantly higher flammability than the taxa from vegetables, weeds, winegrapes, forage crops, grazing herbs, and pasture grasses and legumes (Fig. 3). Moreover, significant variation in flammability was also observed between the growth forms and between the families of the taxa (Table A.1, Figs. A.3 & A.4). Trees were the growth forms that was most flammable followed by shrubs and grasses, whereas forbs and lianas were the least flammable. Among the families, taxa from Rosaceae were the highest in flammability followed by the family Ericaceae and Oleaceae, whereas taxa from the other families were low in flammability (Fig. A.3). Fuel moisture content was the lowest for cereal crops and fruits with mean

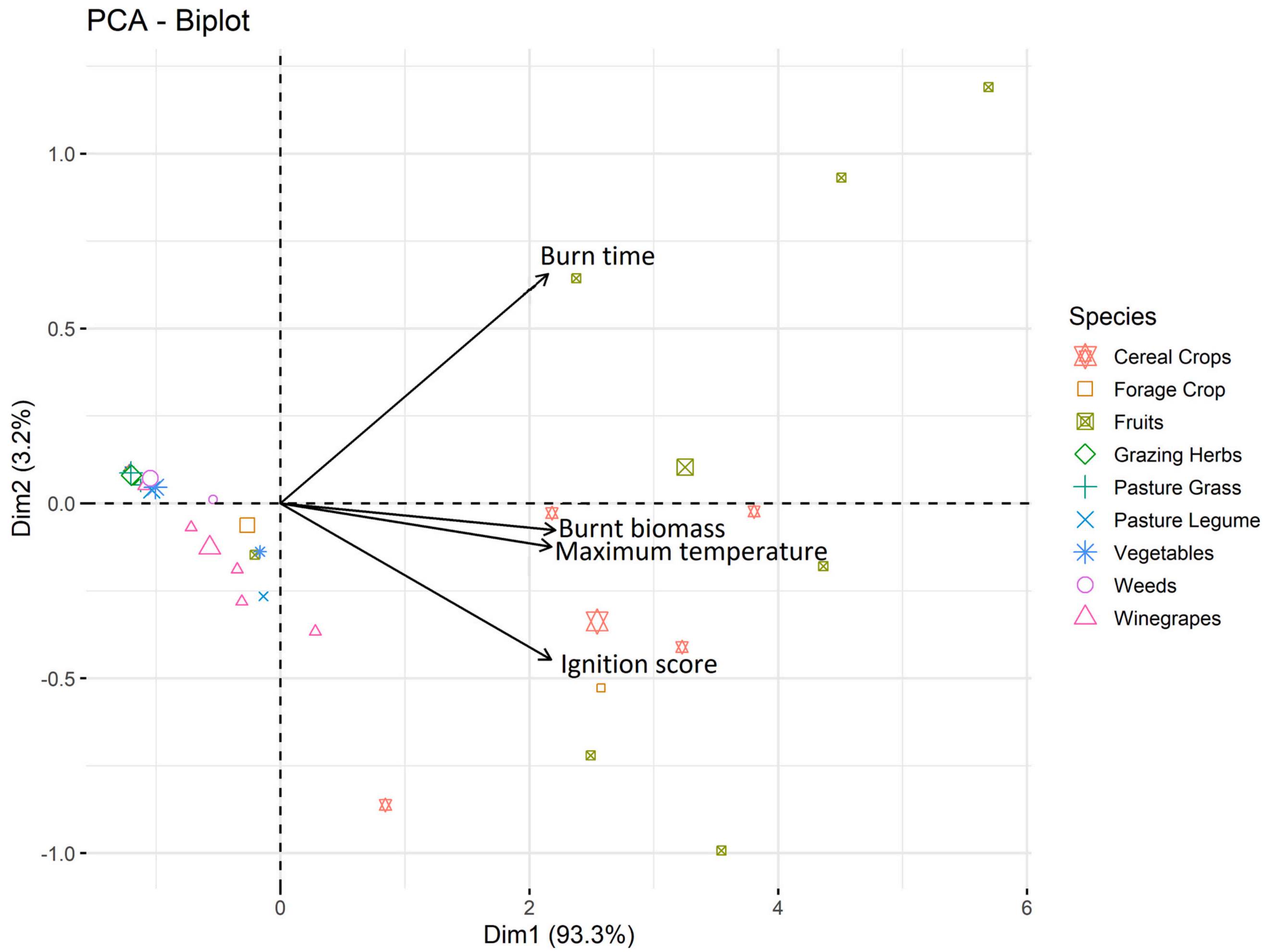

Fig. 1. Principal component analysis (PCA) of the four measured flammability traits (ignition score, maximum temperature, burn time, and burnt biomass) showing the first two components Dim1 (PC1) and Dim2 (PC2) that explained a total of 96.5 % variation in the data. Each symbol indicates the mean score of a taxon while the bigger symbols indicate the mean score of all the taxa from a crop type.

moisture contents ranging from 92 to 117 % on a dry mass basis, whereas the highest fuel moisture content was recorded for forage crops, herbs and vegetables with mean moisture contents ranging from 616 to 641 % on a dry mass basis. Moreover, the moisture loss rate was the highest for the forage crops and fruits, and fuel dead material was the highest for cereal crops (Fig. A.2).

3.2. *Relationships between fuel traits and flammability variables*

The first two axes of the PCA including all fuel traits and flammability variables accounted for 68 % of the total variance (Fig. 4). All flammability variables were positively associated with the first PCA component (ignition score loading = 0.47, maximum temperature loading = 0.46, burn time loading = 0.45, and burnt biomass loading = 0.47), while dead materials (0.15) and moisture loss rate (0.10) were also positively loaded on this component, with moisture content (−0.30) loaded in the opposite direction. Only bulk density (−0.03) had a very weak negative association with the first component. All flammability traits had weak loadings on the second component (ignition score = −0.03, maximum temperature = 0.08, burn time = 0.10 and burnt biomass loading = 0.06). In contrast, all fuel traits had higher loadings on the second component where moisture content and moisture loss rate were positively associated (0.43 and 0.66 respectively), and dead materials and bulk density were negatively associated (−0.37 and −0.46 respectively) (Fig. 4).

The correlation matrix showed that all fuel traits except bulk density were significantly correlated with the flammability variables (Fig. 5). PC1 of the flammability PCA (Fig. 1) was positively correlated with percentage retention of dead materials and the moisture loss rate, and negatively correlated with moisture content (Fig. 5). PC2 was only significantly correlated with moisture content. All flammability variables had a significant negative correlation with fuel moisture content and a positive correlation with both fuel dead materials and moisture loss rate, whereas maximum temperature was significantly negatively correlated with fuel bulk density (Fig. 5).

4. Discussion

The agricultural landscape is a complex land-use system consisting of diverse communities of plant species that differentially influence the spatio-temporal patterns of fire behaviour of the surrounding ecosystems. The primary aim of our study was to assess the flammability of different species grown in agricultural landscapes to identify suitable low flammability taxa for redesigning landscape to help fight wildfires in an increasingly fire-prone world. By quantifying the shoot- and whole-plant flammability of 47 taxa commonly found in agricultural areas, we showed that flammability varied widely between species, crop types and growth forms. Such strong variation of flammability between agricultural species' suggests that the selection of suitable low flammability species and growing them strategically within the agricultural

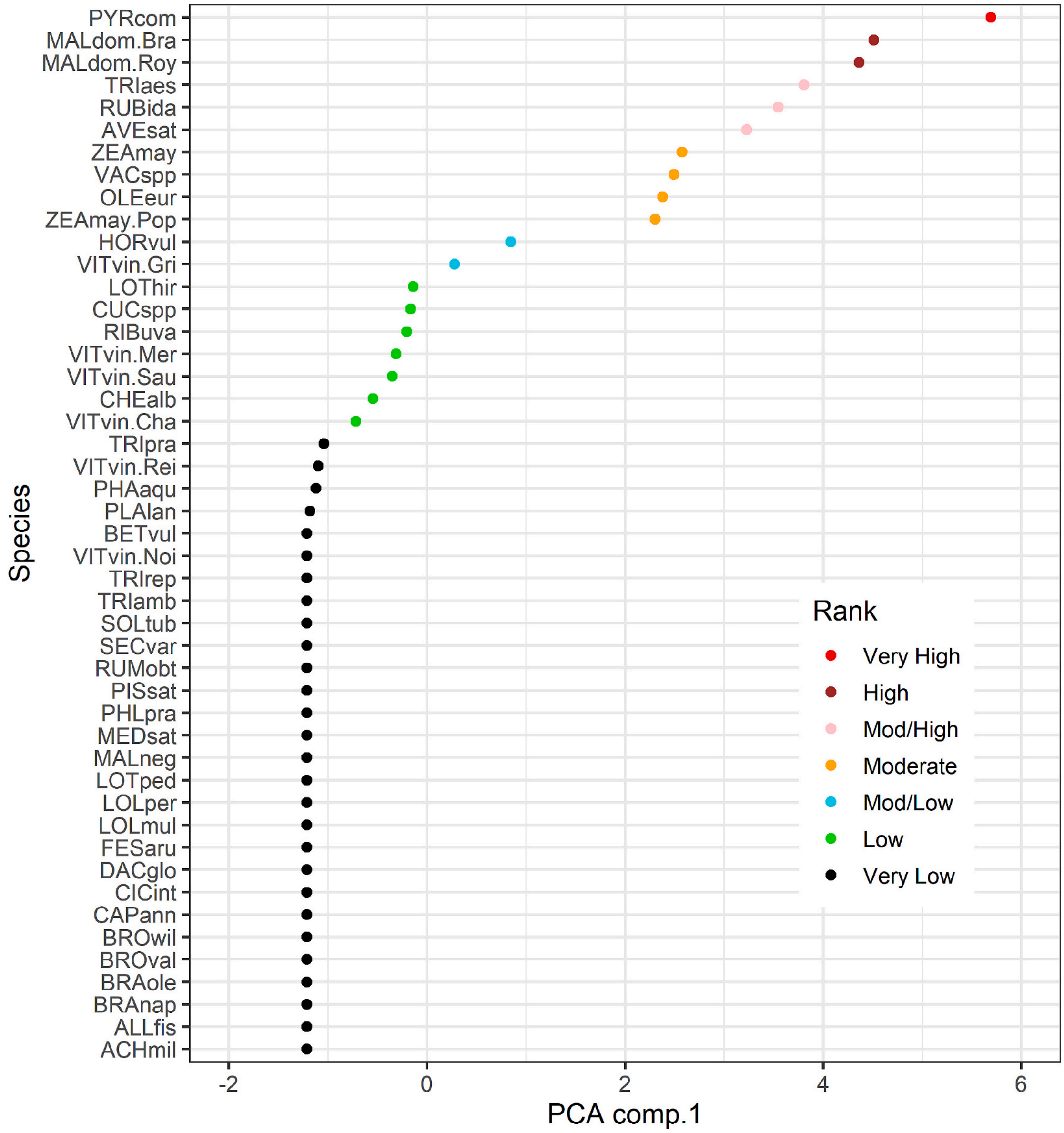

Fig. 2. Flammability rankings for 47 taxa determined by the first axis of the principal components analysis (Dim1: PCA comp. 1) on all the flammability variables (Fig. 1). Taxa were assigned to flammability categories using k-means clustering. See Table 1 for taxon codes.

landscape can be a useful tool to reduce the fire hazards and impacts of wildfires in productive agricultural systems. However, other factors such as local climatic conditions, soil conditions, and agricultural practices (e.g. irrigation) may influence the flammability of a given species (Narog et al., 1991; Cui et al., 2023). Therefore, it is important that in other temperate regions where these conditions differ from our study site, the flammability rankings reported here are confirmed by further testing using the inexpensive, yet effective method that we used. Moreover, the approach that we describe here could also be applied in other agricultural regions globally, such as the tropics (e.g., Zanzarini et al., 2022).

4.1. Plant flammability patterns between taxa and crop types

The taxa we tested in this study showed great variation in their flammability characteristics, measured as to how fast they ignited, how much temperature they released, how long they burned, and how much of the biomass was consumed. Variations in flammability among species have already been reported in different biomes and ecosystems (Calitz et al., 2015; Simpson et al., 2016; Wyse et al., 2016; Padullés Cubino et al., 2018; Santacruz-García et al., 2019; Zanzarini et al., 2022; Murray et al., 2023) and this study further enhances those findings by showing evidence of variation in species flammability in an agricultural landscape. Moreover, the strong variation of flammability between taxa from different crop types can be useful to identify and classify fuel hazards for many species to create fire-resilient landscapes. For example, species of vegetable crops, grazing herbs, pasture grasses, and pasture legumes in this study were very low in flammability indicating their minimal fire risk in the agricultural vegetation community. Variation in the flammability of species was also found between different taxonomic families and growth forms. Taxa from Ericaceae and Rosaceae were highly flammable compared to other families (see Fig. A.3) whereas trees were the most flammable and forbs were the least flammable growth form. This was similarly observed by Cui et al. (2020) who demonstrated that species of the family Ericaceae had higher flammability among the families whereas forbs species had lower flammability among the growth forms when comparing the flammability of 194 species.

Low flammability of forbs compared to other growth forms was

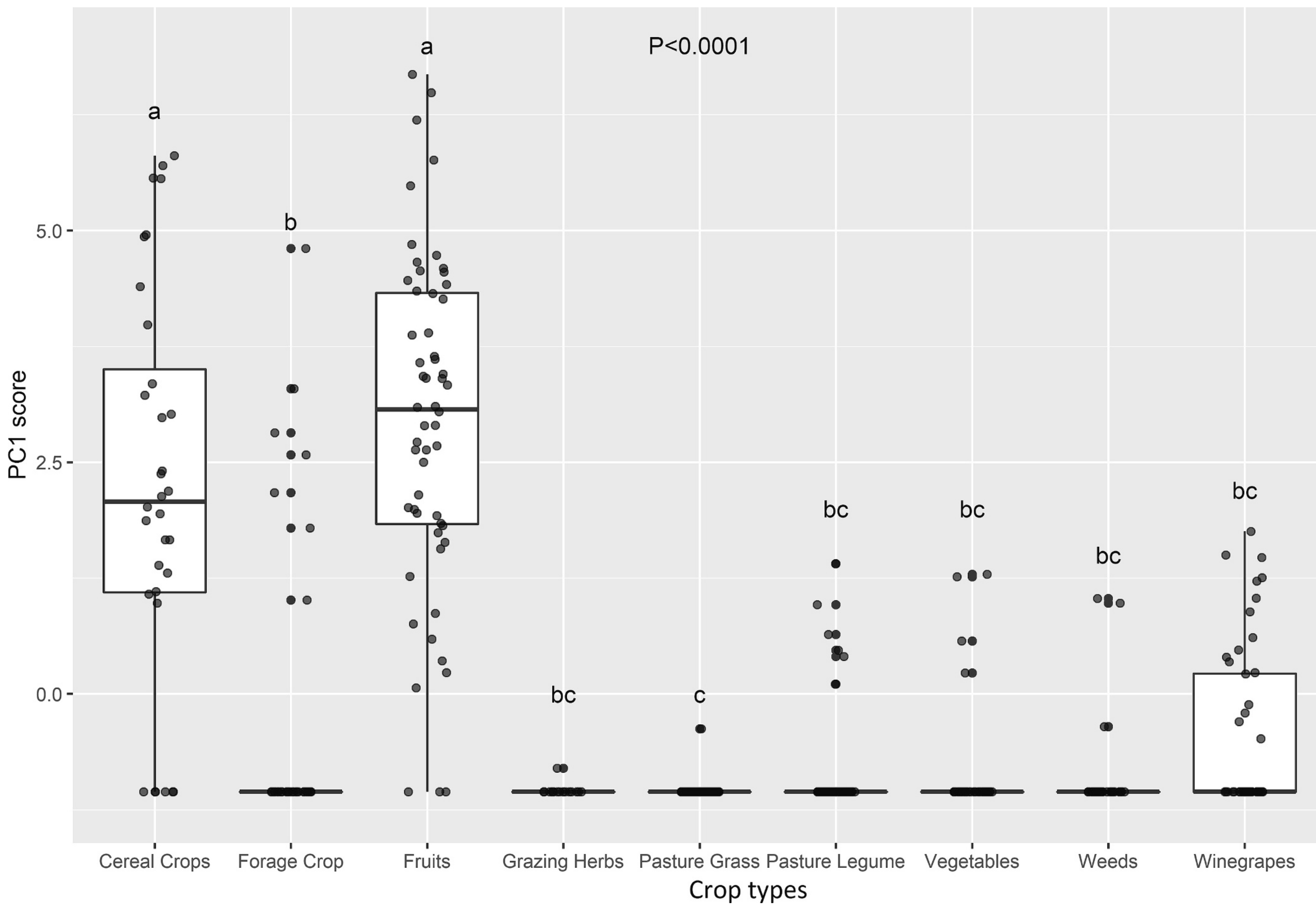

Fig. 3. Boxplots visualising the flammability of the taxa from nine different crop types. Different letters denote significant differences among groups (post hoc Tukey's test, $P < 0.05$). PC1 scores indicating the flammability of the taxa extracted from principal component analysis (Fig. 1), with higher scores indicating higher flammability.

observed in earlier studies (Padullés Cubino et al., 2018; Wragg et al., 2018; Cui et al., 2020), which is likely due to their high tissue moisture content and low fuel biomass that reduces their ability to burn and spread fires. Grass species were the most variable in their flammability among the growth forms, where some were high in flammability (i.e. cereal crops) and some were low in flammability (i.e. pasture grasses). Interspecific flammability variation among grasses has been reported in both savanna and tussock grasslands (Simpson et al., 2016; Padullés Cubino et al., 2018), and this contrasting variation in flammability likely drives differences in fire behaviour of grass communities worldwide, with more palatable grasses being less flammable and less palatable grasses being more flammable (Cardoso et al., 2018; Simpson et al., 2022).

4.2. Relationships between fuel traits and flammability

All fuel traits measured in this study were significantly associated with flammability, while fuel moisture content emerged as the strongest among them, bolstering extensive evidence of this trait being a key determinant of species flammability. Fuel moisture content has been identified as the most important trait to drive the flammability of the species in the trait-flammability literature (Ganteaume et al., 2013b; Popović et al., 2021 and the references therein; Scarff et al., 2021). In our study, the finding of very low flammability in species with a high fuel moisture content such as vegetables, forage crops, and legumes is consistent with the extensive body of literature showing a strong negative correlation between flammability and moisture content (Ganteaume et al., 2012; Murray et al., 2013; Fares et al., 2017; Grootemaat et al., 2017). We also demonstrated that faster moisture loss of the species makes them more flammable. The higher flammability of species with high moisture loss rate was recorded by Padullés Cubino et al. (2018) who demonstrated that species from tussock grasslands that lost moisture faster were high in flammability. Globally, agricultural landscapes are particularly vulnerable to increased drought and heatwaves due to climate change (Haile et al., 2020; Balting et al., 2021), which are likely to drive out moisture faster from crops and managed grasslands, elevating the risk of fire occurrence by increasing species flammability. Moreover, our finding of higher flammability from agricultural plant species with high dead materials is consistent with other studies that showed species with a high percentage of dead material are often associated with high flammability, due to their low moisture content, and hence lower energy required to achieve combustion (Schwilk, 2003; Bond and Van Wilgen, 2012; Burger and Bond, 2015; Dent et al., 2019). The cereal crops tested here (wheat, oat, popcorn, sweet corn) had higher percentages of dead material, which probably elevated their flammability compared to other species. However, the most flammable species (pear, apple) had among the lowest percentage of dead materials. Higher flammability of these fruit crops may have been driven by the presence of various phenolic compounds in their leaves (Rana et al., 2016; Wojdyło et al., 2021) as higher leaf secondary compounds have been associated with higher flammability (Ormeno et al., 2009; Pausas et al., 2016).

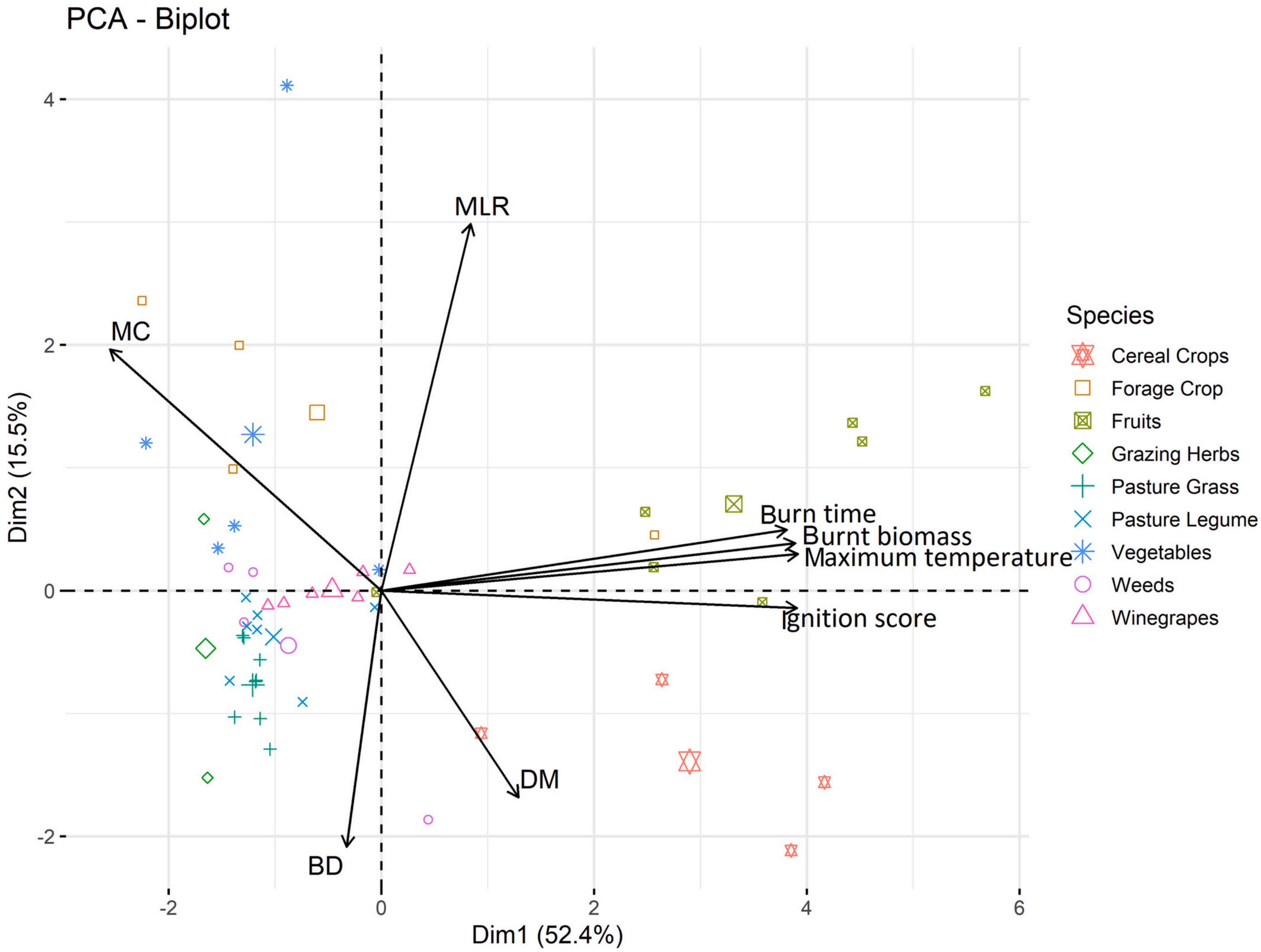

Fig. 4. Principal component analysis (PCA) of the four flammability variables (ignition score, maximum temperature, burn time, and burnt biomass) and fuel traits (MC: moisture content; MLR: moisture loss rate; BD: bulk density; DM: dead materials) showing the first two components that explained 67.9 % variation in the data. Each symbol indicates the mean score of a taxon while the bigger symbols indicate the mean score of all the taxa from a crop type.

4.3. Guidelines for fire management in agricultural landscapes

Changes to agricultural practices and diversifying agricultural production have been identified as emerging approaches to managing wildfire based on the assumptions that they can reduce flammable fuels, disrupt fuel continuity through maintaining a mosaic landscape, have inherently higher moisture content due to their exposure to frequent irrigation, and that the species involved are less flammable (Khabarov et al., 2016; Moreira and Pe'er, 2018; Kelly et al., 2020). Agricultural systems in high fire-risk locations could act as firebreaks and reduce the spread of fire and the total area burned (Lloret et al., 2002; Loepfe et al., 2012). Here, we have demonstrated that many taxa from our temperate agricultural landscape were low in flammability, confirming the potential of agricultural plants to help mitigate fires.

Some studies have tested the idea of using crops and pastures as firebreaks though there has been no widespread screening of the flammability of a wide range of species found on agricultural lands. By comparing the characteristics of pineapple crops (*Ananas comosus*) with herbaceous legumes, such as *Desmodium ovalifolium* (tropical clover) and *Arachis* sp. (peanut), as firebreak hedgerows, Xaud et al. (2009) demonstrated the value of pineapple hedgerows in stopping experimental fires in agricultural landscapes in the Amazon region. Similarly, a field study in Alberta, Canada by Baxter and Woosaree (2013) demonstrated that three pasture species, rocky mountain fescue (*Festuca saximontana*), white clover (*Trifolium repens*), and yarrow (*Achillea millefolium*) were very effective in reducing fire intensity, flame lengths and rate of spread compared nearby grasslands. They suggested further testing of other agricultural species and also replacing flammable grass species with low flammability herbaceous species in wildland-urban interface areas (Baxter and Woosaree, 2013). We found that white clover, yarrow, and another *Festuca* species, tall fescue (*Festuca arundinacea*), were all very low in flammability, further supporting their use in green firebreaks. Another pasture species alfalfa/lucerne (*Medicago sativa*, incorrectly labelled as *Trifolium pratense* in their paper), was suggested for use in green firebreaks in New Zealand by Jolly and Guild (1974) and is another very low flammability species identified by our study. Moreover, other vegetable crops, pasture grasses, and pasture legumes that we have identified as low to very low flammability could be used as green firebreaks globally where they are biophysically-ecologically suitable to grow. The low flammability of the pasture grasses, pasture legumes, and grazing herbs was probably due to the high moisture content of their leaves. While this means that such species can be useful for fire mitigation when they are green, if they dry off as part of their growth patterns or agricultural management they could then pose a fire hazard to the surrounding ecosystems (Parrott and Donald, 1970; Cheney and Sullivan, 2008). Many crops, pastures, and legumes grown within agricultural landscapes dry out at a particular time of their life cycle, growing season, or when exposed to extreme

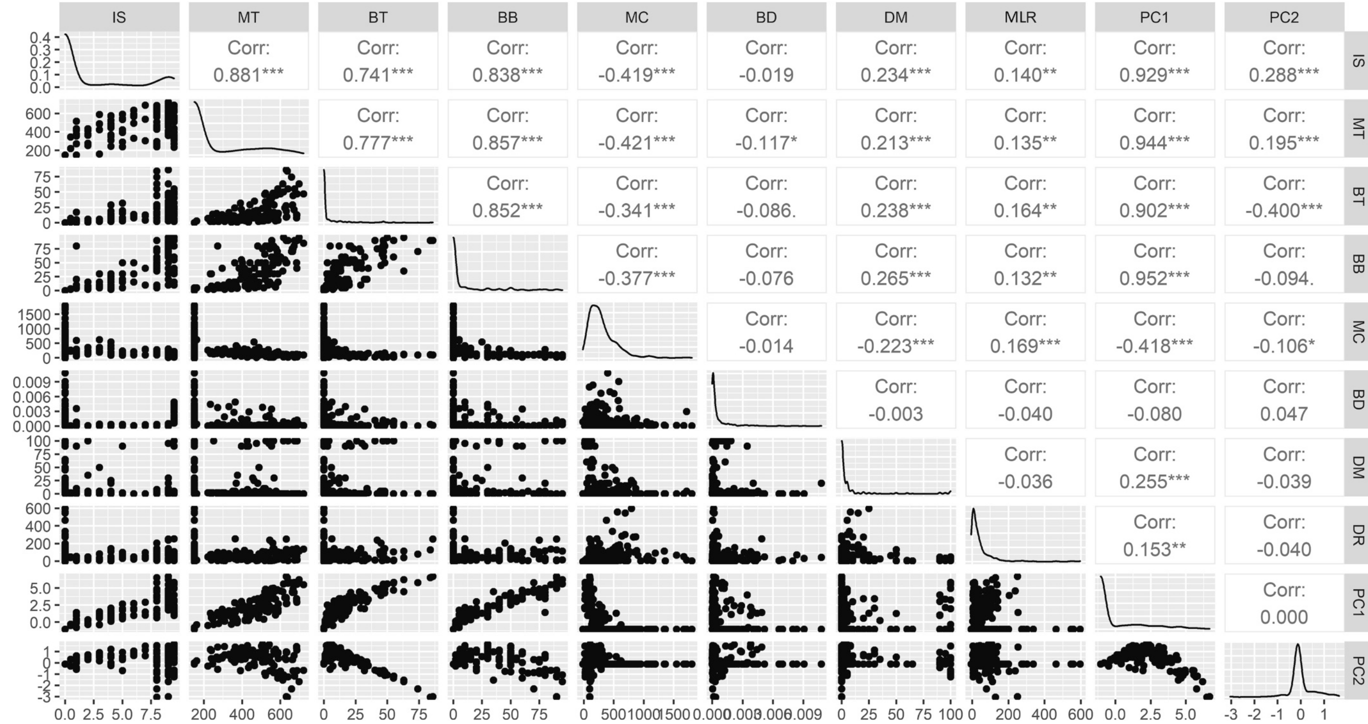

Fig. 5. Correlation matrix visualising the Pearson's correlation coefficient between the flammability variables (IS: ignition score, MT: maximum temperature, BT: burn time, BB: burnt biomass), fuel traits (BD: bulk density, DM: dead materials, MLR: moisture loss rate and MC: moisture content) and principal component scores (PC1 and PC2). Statistically significant correlations are marked by an asterisk. *, **, *** Significant at $P \leq 0.05$, 0.01 and 0.001, respectively.

drought. Thus, testing their flammability at different times of the year to fully understand the fire hazard status of various agricultural plant species and their potential use for fire protection is required. For example, cocksfoot/orchard grass (*Dactylis glomerata*) which is often considered as low flammability (as per our findings), can be a serious fire hazard when dried off in summer, as suggested by Jolly and Guild (1974). Furthermore, well-maintained and irrigated orchards with various low flammability fruit plants can act as a barrier to wildfire spread (Moreira et al., 2011; Depietri and Orenstein, 2020).

Some of the commonly grown fruit trees and shrubs (apple, pear, raspberry, blueberry) that we tested in this study were highly flammable and thus pose a significant fire hazard in fire-risk and fire-prone areas. Therefore, care should be taken when considering growing these species in fire-prone landscapes by ensuring regular watering, clearing of dead biomass or ground litter, and surrounding them with low flammability species. We also suggest quantifying the flammability of other fruit crops (e.g., citrus, kiwifruit, stonefruit) to increase the diversity of options for inclusion in green firebreaks in fire-prone regions. Grape varieties that we tested (e.g., Chardonnay, Merlot, Pinot noir, Sauvignon Blanc and Riesling) had low to very low flammability, suggesting their suitability for utilization as green firebreaks. However, any grape crops used as green firebreaks may have to be treated as sacrificial crops at least for that season, as smoke taint may greatly impact their value as a crop in such circumstances (Kennison et al., 2008; Noestheden et al., 2018).

4.4. *A potential design of a farm landscape with low flammability species as firebreaks*

The main objective of a firebreak is to keep a fire under control and stop it from spreading (Curran et al., 2017). Green firebreaks should therefore be deliberately positioned to use current fuel barriers like roads, rivers, lakes, and hills in order to segregate areas at risk of fire (Cui et al., 2019). We have developed a guideline for a potential firewise (i.e., low fire threat) agricultural landscape in a mixed cropping farm scenario (Fig. 6). It is to be noted that Fig. 6 shows a general variety of crops and cropping locations and is not restricted to any one season of the year. Furthermore, this planting approach is designed primarily from the point of view of fire mitigation, other factors (local environmental conditions, economics of crop returns, and the desire for enhanced biodiversity outcomes) would all mean that this scheme would need to be amended accordingly. Also, the approach should be accompanied by field-based fire experiments to assess whether such redesigned landscapes do suppress fire behaviour sufficiently to protect homes and infrastructure. Furthermore, green firebreaks should be used in conjunction with other fire suppression methods for best outcomes (Curran et al., 2017). Irrespective of these caveats, Fig. 6 shows what might be possible to use in planting design to reduce fire hazards on a farm.

Firstly, the farm is bounded by strips of low flammability native tree species (also acting as shelterbelts) along with tracts of low flammability pasture grasses or legumes adjacent to the belt of trees (Fig. 6). It will help in protecting the farm from the prevailing winds and fires coming from those directions. It will also protect neighbouring properties from a fire starting on the property in question. A similar mix of strips of low flammability native trees with adjacent tracts of pasture grasses or legumes are used to border the higher flammability commercial crops, fruit trees (orchards) and houses within the farm. Recent field experiments in Gabon, central Africa, found that the change in fire intensity between a grassy savannah and a rainforest patch is partly driven by the change in grass composition, with less flammable grasses closer to the forest (Cardoso et al., 2018). By incorporating tracts of low flammability pasture grasses or legumes adjacent to the belt of native trees, it is intended to mimic a similar change in fire behaviour (i.e., decrease in fire temperature and intensity) for the landscape (Fig. 6). Not only does this mix act as a 'buffer zone' by providing an extra layer of protection to the farm, crops, and houses, but these strips of lower flammability species can act as wildlife corridors, amplifying the biodiversity values of the farm.

There is a higher risk of an intense fire if the fire reaches highly flammable crops. For example, wheat (*Triticum aestivum* L.) was among

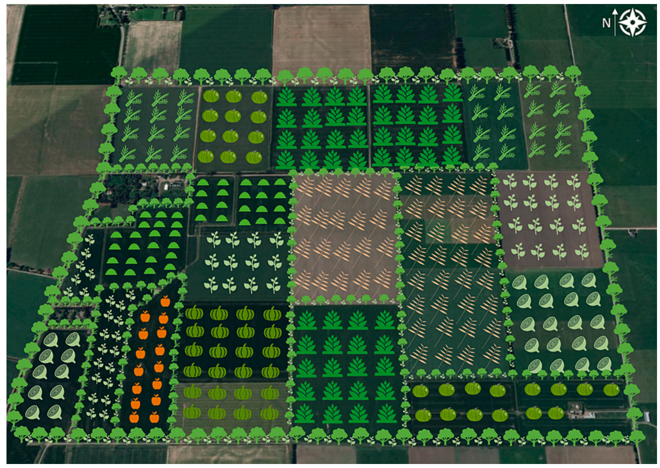

Fig. 6. A fire-wise mixed cropping farm system showing a general variety of crops and cropping location and is not restricted to any one season of a year. Key:

Icon	Crop type	List of species that could be used with their flammability rankings
	Low flammability native tree/shelter belt/native shrubs species	Any suitable native species that are low in flammability and locally common
	Moderately High/Moderate flammability cereal crop species	'Moderately high': Wheat (*Triticum aestivum* L). 'Moderate': Barley (*Hordeum vulgare* L.), Oats (*Avena fatua* L.), Popcorn (*Zea mays* var. *everta*),
	Low flammability forage crop species	'Very Low': Kale (*Brassica oleracea* L. var. *Sabellica), Fodder beet (Beta vulgaris 'Mangelwurzel'),* Rapeseed *(Brassica napus* L.)
	Low flammability pasture grass species	'Low': Pasture Brome (*Bromus valdivianus* Phil.) 'Very Low': Cocksfoot *(Dactylis glomerata* L.), Italian ryegrass (*Lolium multiflorum* Lam.), Perennial ryegrass (*Lolium perenne* L.), Phalaris/bulbous canary-grass (*Phalaris aquatica* L.), Prairie grass (*Bromus willdenowii* Kunth.), Tall Fescue (*Festuca arundinacea* Schreb.), Timothy grass (*Phleum pratense* L.)
	High/Moderately High flammability fruit crops/orchards	'High': common pear (*Pyrus communis* L.), 'Moderately high': Apples (*Malus domestica.* 'Braeburn', *Malus domestica.* 'Royal Gala'), 'Moderate': olives (*Olea europaea.* 'Barnea'), raspberries (*Rubus idaeus* L.)
	Low flammability pasture legume and grazing herb species	'Very low': Caucasian clover (*Trifolium ambiguum* M.Bieb), Coronilla/crown vetch (*Securigera varia* (L.) Lassen), hairy canary-clover (*Dorycnium hirsutum* L.), lotus/big trefoil (*Lotus pedunculatus* Cav.), lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), white clover (*Trifolium repens* L.), chicory (*Cichorium intybus* L.), ribwort plantain (*Plantago lanceolata* L.).
	Low flammability vegetable crop species	'Very low': Squash (*Cucurbita spp.* L. (*maxima, moschata, pepo*)), potatoes (*Solanum tuberosum* L.), spring onions (*Allium fistulosum* L.), dwarf snow peas (*Pisum sativum* L.), bell peppers (*Capsicum annum* L.).

the most flammable crops tested here and hence poses a high fire threat. However, if this highly flammable crop is planted in the middle of a mosaic of low flammability crops (such as low flammability vegetable crops, forage crops, pasture grasses and legumes) in the inner paddocks of the farm, it will provide additional protection. Moreover, the higher flammability cereal/commercial crops are planted downwind from the main house that is located on the western edge of the farm to reduce fire threat to that house. Similarly, the highly flammable fruit trees/orchard is also positioned to be distant from houses and other infrastructure. Moreover, despite the high foliage flammability of fruit trees, the fire hazard in the orchard could be mitigated by judicious trimming of lower branches to separate ground and canopy fuels, where this is compatible with the production of such crops.

5. Conclusion

Our study has compared the flammability of plant species commonly found in a temperate agricultural landscape and shows how knowledge of plant flammability can be applied to assess fire hazards and used to design landscapes to combat wildfire. By categorising the flammability of agricultural plant species, this study will enable farmers and landholders to redesign their farms, wherein they may be able to plant any low-flammability species, in areas they deem as high fire hazards. Overall, this knowledge will improve our understanding of the temporal and spatial variation of fire spread and intensity in agricultural landscapes and help prepare for wildfires in the age of rapid global climate change.

CRediT authorship contribution statement

Tanmayi Pagadala: Project development, Investigation, Formal Analysis, Visualization, Writing-Original Draft, Writing-Review and Editing. **Md Azharul Alam:** Project development, Investigation, Formal Analysis, Visualization, Writing-Original Draft, Writing-Review and Editing, Supervision. **Thomas MR Maxwell:** Project development, Writing-Review and Editing, Supervision. **Timothy J Curran:** Conceptualization, Project development, Writing-Review and Editing, Supervision.

Declaration of competing interest

The authors declare that they do not have any conflict of interest that could influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167489.

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