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Human Fire Use and Management: A Global Database of Anthropogenic Fire Impacts for Modelling

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Abstract: Human use and management of fire in landscapes have a long history and vary globally in purpose and impact. Existing local research on how people use and manage fire is fragmented across multiple disciplines and is diverse in methods of data collection and analysis. If progress is to be made on systematic understanding of human fire use and management globally, so that it might be better represented in dynamic global vegetation models, for example, we need improved synthesis of existing local research and literature. The database of anthropogenic fire impacts (DAFI) presented here is a response to this challenge. We use a conceptual framework that accounts for categorical differences in the land system and socio-economic context of human fire to structure a meta-study for developing the database. From the data collated, we find that our defined anthropogenic fire regimes have distinct quantitative signatures and identify seven main modes of fire use that account for 93% of fire instance records. We describe the underlying rationales of these seven modes of fire use, map their spatial distribution and summarise their quantitative characteristics, providing a new understanding that could become the basis of improved representation of anthropogenic fire in global process-based models. Our analysis highlights the generally small size of human fires (60% of DAFI records for mean size of deliberately started fires are <21 ha) and the need for continuing improvements in methods for observing small fires via remote sensing. Future efforts to model anthropogenic fire should avoid assuming that drivers are uniform globally and will be assisted by aligning remotely sensed data with field-based data and process understanding of human fire use and management.

Keywords: fire regimes; land systems; dynamic global vegetation models; meta-study; database

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1. Introduction

The human use and management of fire in landscapes is diverse globally. For example, burning is deliberately used to provide a simple fertiliser in shifting cultivation [1,2], to clear agricultural and forestry residues [3], and to deter pests and regenerate forage in livestock farming [4,5]. Fire management includes intentional activities to directly suppress the risk of fires occurring (e.g., [6]) and limit spread and damage when they ignite accidentally (through firefighting [7]). However, humans also modify fire regimes unintentionally in multiple ways [8], for example by altering fuel loads (through grazing and logging [9,10]) and fuel continuity (through fragmentation of landscape vegetation [11]). Although the long history of human use and management of fire for shaping landscapes around the world has been well examined [12–14], representation of these diverse activities in models of global fire and vegetation has been minimal to non-existent. Underpinning this inadequacy in global modelling is the lack of a systematic empirical basis from which to derive improved representations of human fire use and management globally. In this paper, we present the development and analysis of a global database of anthropogenic fire impacts (DAFI), motivated by the need to better represent the diversity of human fire use and management in global modelling.

At the global scale, fire is most frequently modelled as a component of dynamic global vegetation models (DGVMs)—process-based biophysical models that form the terrestrial biosphere component of general circulation models. The historical emphasis in DGVMs has been representing biophysical processes, with anthropogenic influences considered as external forcings [15,16]. Recent fire-enabled DGVMs have attempted to represent human impacts on fire with simple analytic functions derived from variables readily available at global extent (population density and GDP). A comparison of these fire-enabled DGVMs, the Fire Model Inter-comparison Project [17], found representations of people to be both the most substantial cause of disagreement between models, but also between models and remote sensing observations [18,19]. Not only do current DGVMs have limited ability to reproduce observed patterns of fire use, they have little predictive power because they do not represent the underlying socio-economic process and land management practices that drive human–fire interactions [18,20].

The development of improved functions to better represent the diversity of human fire use and management in DGVMs has been hindered by the lack of appropriate global empirical data. Such a situation may seem surprising given the volume and breadth of research on human interactions with fire. Empirical studies of human fire have been conducted in many different academic fields, including geography, anthropology, land economics and ecology. However, this research is fragmented across disciplinary boundaries, is varied in its methods, and ranges across scales. From the most general perspective, we can distinguish between global studies that characterise human impacts on fire using remote sensing and other broad-scale secondary data (e.g., [21–24]) versus local studies that examine cases of human use and management of fire in particular locations and contexts using field-based data collection (e.g., [25–27]). With few exceptions (e.g., [10,28]), advances in understanding of human fire at the local-scale have not been integrated with analysis of global-scale biophysical data [29]. Despite the crucial role of fire in land systems, a review of meta-analyses in land system science did not identify any such studies focused explicitly on fire use [30]. Thus, although there has been much field-based and local-scale study of human fire, efforts to synthesise data from these studies to advance global-scale understanding have restricted their focus on traditional fire use, whether in a hunter-gatherer and pastoralist [31], or small-holder context [32]. If we are to better represent human fire in DGVMs, for example by identifying and parameterising types of human agency (e.g., [33]), we need improved global empirical data on human fire use and management.

Here, we present our meta-study approach, collating data and publications on field-based and local-scale studies, to develop a global database of anthropogenic fire impacts (DAFI). As the ultimate goal of this work is to improve the empirical basis for advancing representation of human fire impacts in DGVMs, the emphasis of DAFI is on the quantitative characterisation of key modelling variables, including fire size and ignition frequency, and how these variables vary spatially globally. Furthermore, our characterisation aims to account explicitly for how fire practices vary categorically, due to differences between land systems and socio-economic conditions. This categorisation will provide the basis for agent-based representation of human activity and behaviour in DGVMs in a way that will allow simulated projections. We first describe the conceptual framework used to structure our meta-study before presenting analysis of the key variables included in the database. Subsequently, we discuss the ongoing challenges to improving data on human fire use and management for global modelling.

2. Materials and Methods

2.1. Conceptual Framework for Meta-Study

Given the fragmented literature on human fire, establishing an empirical basis for improving representation of human fire in DGVMs requires synthesis of not only evidence from multiple disciplines, but also diverse types of data derived from a range of qualitative and quantitative methods. This situation is common in socio-ecological studies and approaches to synthesise such variegated case-study sources have been developed [30,34].

Our approach here falls under the category of 'site-comparison' in the range of meta-study approaches [34].

Previous attempts to conduct formal meta-analyses of fire using specific search terms have tended to report limited numbers of papers identified for human fire use compared to the wider fire management and ecological literature [35,36]. This is likely because human fire is often studied as incidental to, or as a function of, a separate subject. For example, deforestation fires are frequently studied in a context of wider discourse about biodiversity loss (e.g., [5,37,38]), shifting cultivation fire is often investigated in the context of political ecology or sustainable development discourses (e.g., [1,39,40]), and crop residue burning is commonly examined in the context of the consequences of the practice for air quality and respiratory health (e.g., [41]). Furthermore, even when fire is the primary focus of a study, differences in terminology can arise across subject disciplines. For example, direct studies of crop residue burning can report findings for specific commodities (rice, wheat, etc.) or in more general terms (e.g., 'agricultural burning', 'straw use'). These issues challenge development of a comprehensive and systematic meta-analysis methodology, and so we defined a conceptual framework to structure our iterative literature search.

Many previous frameworks for understanding human fire have identified the importance of the socio-economic context in which people inhabit and manage their landscape for understanding fire-related land management practices. For example, an environmental history perspective provides a qualitative narrative of changing fire practices broadly along a trajectory of industrialization [12], a socio-ecological approach has been used to extend the concept of ecological fire regimes to emphasise the importance of fire and land use objectives [42], while a political ecology perspective has highlighted the key distinction between anthropogenic fire regimes in pre-industrial vs. industrial eras [43]. Others [44] identified a transition from natural to managed landscapes in empirical signatures of burned area from remote sensing data. All these frameworks recognise the importance of land use and land management practices for understanding fire regimes. In land system science, regimes of activities from subsistence to intensive resource use have been delineated (e.g., [45,46]).

Our framework builds on this previous work to account for human fire use and management as a combination of land use objectives on the one hand and fire practices dependent on management intensity and attitudes towards fire on the other hand. Management intensity and fire attitudes are grouped generally into 'Pre-Industrial', 'Transition', 'Industrial' and 'Post-Industrial' anthropogenic fire regimes (AFRs). Pre-Industrial AFRs are characterised by active use of fire and limited mechanisation in land management. Industrial AFRs are the inverse, with negative attitudes towards fire use and fire replaced by mechanisation and chemical fertilisers for manipulating and managing land. Transition AFRs may adopt different elements of other regimes and are often characterised by the use of fire to move from lower intensity to higher intensity management of land. Finally, Post-Industrial AFRs are those characterised by an appreciation for the importance of fire as an ecological process and/or the need to manage land that has become marginal in economic terms (and therefore generally have a lower management intensity than Industrial AFRs).

We recognise that previous attempts to classify human fire use and management in the context of land management intensity have proved controversial [8,29]. In particular, the argument that it is possible to denote 'phases' of human fire use that deterministically follow from another has been criticised [29]. Our AFRs are proposed only as an attempt to capture the broad-scale impact of management intensity on fire regimes for modelling, something which is acknowledged by critics of wider claims about the inherent 'phases' of human fire management [29]. The sequence of our AFRs in a landscape need not be mono-directional, as demonstrated by the reintroduction of small-holder agriculture ('Transition') from intensive agriculture ('Industrial') at the collapse of the Soviet Union [47]. Further, each of our AFRs might result in differing fire practices between land use contexts (e.g., forestry vs. crops vs. livestock) and may exist alongside (or conflict with) other regime types in the same geographic region. Such coexistence of AFRs can be seen in Indonesia, for example, where fire use for hunting and fire-exclusionary intensive palm-oil plantations are found in close proximity [48].

Cross-referencing AFRs and land uses established broad groupings of concepts and literature around which to initiate and frame literature searches from existing reviews or foundational papers (Table 1) and search-engine terms (Web of Science and Google Scholar, see Appendix A). These groupings are purposively chosen to support the ultimate aim of our work—parameterisation of 'agent types' for improved representation of human fire use and management in DGVMs. However, many of the fields in the database developed (e.g., fire size) can be used independently of these groupings (e.g., cross-referencing against biomes using spatial location).

Table 1. Indicative land management practices used to structure literature review with exemplary references.

AFR	Land Use		
	Forestry	**Livestock**	**Crops**
Pre-Industrial	Hunting–Gathering [49]	Pastoralism [50]	Swidden [51]
Transition	Logging [9]	Extensive Ranching [52]	Small-holdings [53]
Industrial	Managed Forests [54]	Intensive Ranching [55]	Intensive Farming [56]
Post-Industrial	Pyro-diverse Mgmnt [57]	Subsidised Grazing [58]	Abandoned [59]

Our literature search took an iterative ('snowball') approach to ensure multiple 'hidden' literature populations could be identified [60]. This approach is useful given that the disciplinary fragmentation and methodological diversity of the human fire literature has led to multiple frameworks for understanding human–fire interactions and inconsistent terminology for describing them. Together, this is indicative of unsystematic prior understanding of the subject and prevented the use of a set of standard literature search terms [61]. Foundational papers on fire use and management were used as the starting point for reviewing literature relevant to each combination of AFR and land use, but when not available for a given grouping, non-fire land systems papers were used (e.g., [62]. Geographic representativeness was pursued by adding country names from underrepresented geographic regions to the specific search-engine terms. The focus of the review was studies collecting data for 1990–2020, but data for earlier periods were included if they were reported in studies alongside post-1990 data (and for shifting cultivation, studies from the late 1980s were included to ensure broader spatial coverage).

2.2. Human Fire Variables

Data were collected from studies in the literature for variables associated with three key components of anthropogenic fire regimes:

- *Fire use*, including the purpose of use and fire sizes;
- *Fire suppression*, including the types of actions taken;
- *Fire policies*, including those adopted by government and non-governmental institutional actors.

Studies were considered for inclusion in the database if they reported on at least one of these components. Information about study period, location and land use, including the presence and rates of biomass (fuel) removal, was also collected and used to define case studies. For example, a study reporting data from two locations would be recorded as at least two case studies, but this might be split further if there was a pronounced change in land use at these locations during the study period (e.g., before and after the reintroduction of Aboriginal landscape fire in Northern Australia [63]). This approach allows data about the context of human fire behaviours to be recorded consistently. Furthermore, individual instances of fire use, suppression and policy implementation within a case study were identified, with the potential for multiple instances per case study. Studies, case studies and instances of fire use, suppression, and policy thus have unique identifiers in DAFI. Information for our variables was often provided by studies in different formats, but data were recorded in DAFI with a consistent type for each of our variables across all studies (see [64] for all variables, their data type and description). Similarly, although some studies did not directly report values for our variables, where possible we estimated values from information provided (see examples below). For some variables we were able to distinguish between intended vs. actual activities, which could be useful for understanding the impact and role of policies on fire regimes.

2.2.1. Fire Use

Data on fire use distinguish fires as being either deliberate or accidental, and fires started deliberately that grew beyond their original purpose and intended size were recoded as 'escaped'. The intended purpose of deliberate fires was recorded, along with the intended and actual fire sizes and land cover types burned. Intended fire purpose can be determined from reported preferences in field interviews (e.g., [65]) or institutional management plans (e.g., [66]). Intentions about fire size can be inferred from crop field size (e.g., [53,67]), or from median patch size in a pastoral or patch mosaic burning system (e.g., [68]). Where inferences about intended fire size were made from proxy variables such as field size, the resulting uncertainty was accounted for by recording data in binned ranges. Actual fire sizes were recorded from studies that made direct observations of a fire regime. However, studies indirectly investigating fire regimes—such as those from the anthropological literature describing pre-industrial fire practices—rarely report the entire distribution of fire sizes within a study area and instead usually provide summary statistics such as a mean or minimum and maximum value. Therefore, values were identified for minimum, median, mean and maximum fire size and recorded separately in distinct database fields. Ignition frequency and season were also recorded when possible.

2.2.2. Fire Suppression

Information on fire suppression is presented in the literature in both quantitative (e.g., percentage of the land where fuel treatments were prescribed, [6]) and qualitative formats (e.g., use of improvised fire beaters [35]). Furthermore, no existing framework could be found at the global scale to structure the recording of such information. Therefore, a four-point (0–3) ordinal scale was adopted to capture suppression from no effort, through limited (ad hoc) or moderate (traditional) to intensive efforts. Similar scales have been co-developed with fire suppression experts (e.g., [69]). Here, limited effort implies unplanned or ad hoc measures, whereas intensive effort is highly mechanised and planned. The intermediate moderate category principally captures fire management based on traditional fire knowledge (e.g., [27,70]), but is also used to account for fire suppression that uses a limited degree of mechanisation and planning (e.g., [35,71]). The scale was used here to characterise three key components of suppression actions:

- *Control* actions taken immediately prior to lighting a deliberate fire to control its behaviour;
- *Prevention* actions to modify the fire regime, particularly to prevent catastrophic wildfires;
- *Extinguishing* actions to put out active wildfires.

2.2.3. Fire Policy

Fire policy data are overwhelmingly reported in a qualitative format, typically describing the history and rationale of a particular policy, and possibly the range of actors involved in forming it. Policies are recorded in DAFI if they involve either legislative bans or restrictions on fire use short of an outright ban, as well as economic incentives that encourage or discourage fire use. Policy actors include national governments, state and local government, non-governmental organizations, private companies, and supranatural bodies such as the European Union and United Nations. During literature review, three underlying rationales for fire policy measures were found to occur regularly and provide a coherent framework to capture the driving force behind policy choices. These rationales were:

- *Environmental*, including efforts to protect biodiversity, ensure water quality and prevent soil erosion;

- *Economic*, often with the aim of eradicating fire use to encourage agricultural intensification, as well as incentives to clear primary forest for economic development;
- *Health*, principally to improve air quality but also to protect people from death directly due to wildfire.

2.3. Database Summary and Analysis

At the time of publication DAFI contains data from 1809 human fire-related case studies collated from 504 sources. Data are overwhelmingly from academic publications (94% of case studies) but were also from reports produced by governments and NGOs (5%). Case studies used data exclusively from Field Studies (39% of case studies), Institutional Data Repositories (23%), Remote Sensing (4%), Literature Review (7%) or a combination (24%) of these data sources. The remaining case studies (3%) used expert elicitation, media reports, archival research, and other reports as sources.

Reflecting the fragmented nature of the anthropogenic fire literature, no case study contained data on all variables and data across all DAFI fields are sparse. For example, for reported fire use data, 60% of values were missing, rising to 82% when only quantitative variables are considered. Furthermore, we were able to define an AFR for only 1605 of the 1809 case studies (Pre-Industrial 261, Transition 850, Industrial 300, Post-Industrial 194) as land use information is not always provided or available. The incompleteness of the database means that the number of values used in analyses below varies depending on which aspects of anthropogenic fire are being examined.

Our data analysis below focuses on how human fire variables vary by anthropogenic fire regime, but also geographically and by fire purpose. All analyses are at case-study level unless otherwise stated. The database constructed is freely available in an online repository [64] as is code used for analysis [72]. As further work in this area continues, additional case studies and data may be added to the database, which will be updated as a new version in the online repository (with existing versions archived permanently).

3. Results

3.1. Geographic Distribution

When DAFI data sources are mapped spatially (Figure 1a) we find a prevalence of case studies using institutional data in Europe and North America versus a dominance of field studies in Asia and Africa. Despite measures taken to avoid geographic bias (as described above), it is important to recognize possible under-representation in some regions (e.g., Siberia) due to limited study or publication in the English language (as we discuss further below).

The spatial distribution of AFRs (Figure 1b) indicates a similar distribution to data sources, with a prevalence of Industrial and Post-Industrial regimes in Europe and North America versus a dominance of Transition and Pre-Industrial regimes in Asia and Africa. A Chi-square test for the association between AFR and data source indicates non-randomness (Chi-sq = 608, df = 15, $p < 0.001$) and Primary sources dominate case studies of Pre-industrial (72% of case studies) and Transition (51%) regimes, whereas Secondary sources (principally institutional repositories) are the most frequent data sources for case studies of Industrial (46%) and Post-industrial (30%) regimes.

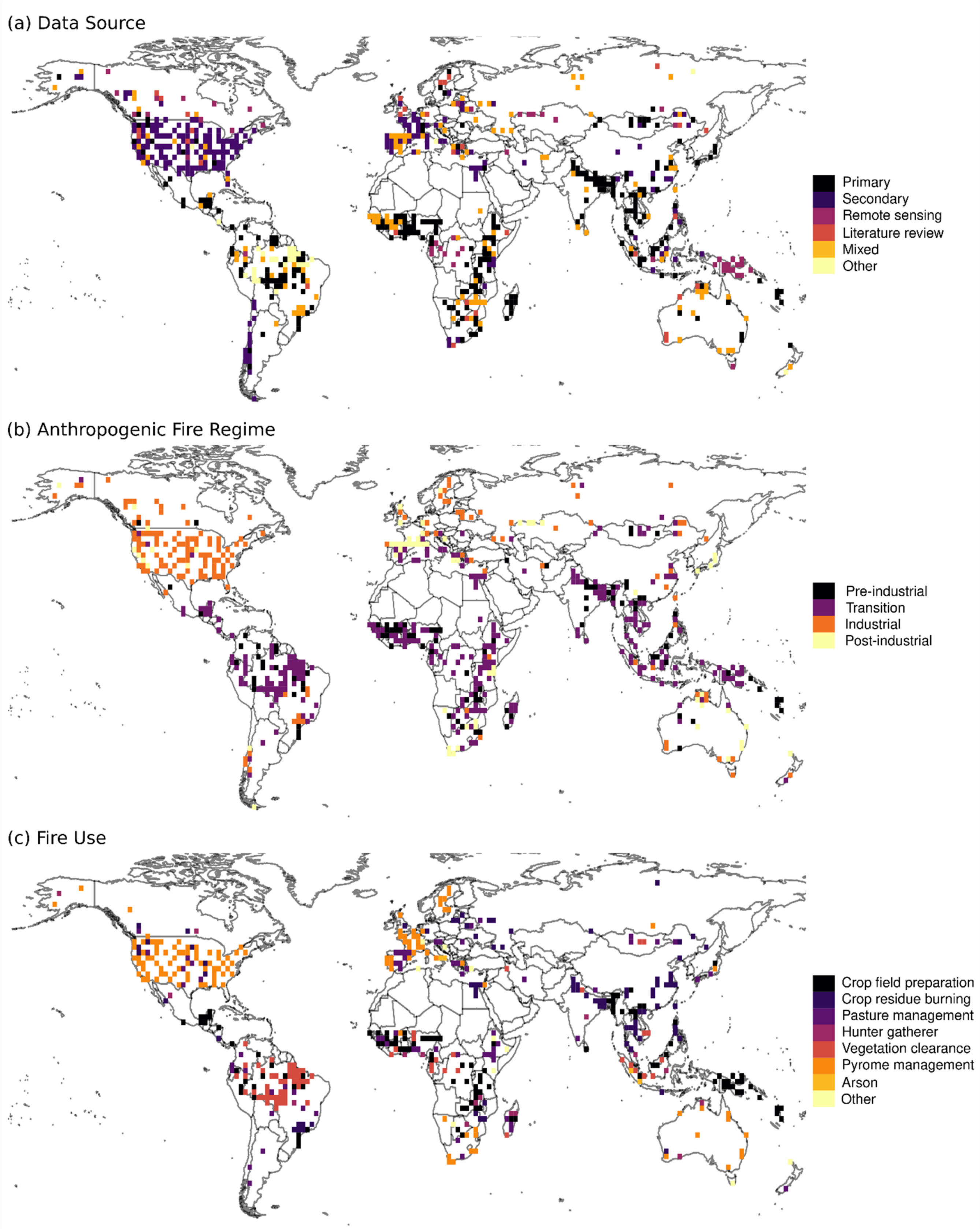

Figure 1. Spatial distribution of (**a**) case study data sources, (**b**) anthropogenic fire regimes and (**c**) fire use. Map grid has a resolution of 2 decimal degrees with the most prevalent source/regime shown for each grid cell.

3.2. Fire Use

3.2.1. Fire Purpose

Overall, 20 anthropogenic fire uses were identified during literature review, but many were closely related (e.g., 'pasture renewal' and 'rangeland management'). After such similar uses were combined (see Supplementary Materials), seven dominant modes of fire use emerged (Table 2) each with more than 100 instances in the database and accounting for 93% of fire instance records. The seven modes of fire use have distinctive quantitative signatures (Table 2), distributions across space (Figure 1c) and prevalence by anthropogenic fire regime (Figure 2). For example, although (shifting cultivation) crop field preparation and (non-shifting) crop residue burning have relatively similar mean size, the short fire-return period and high density of fields of the latter compared to the former combine to produce a greater proportional mean burned area (Table 1).

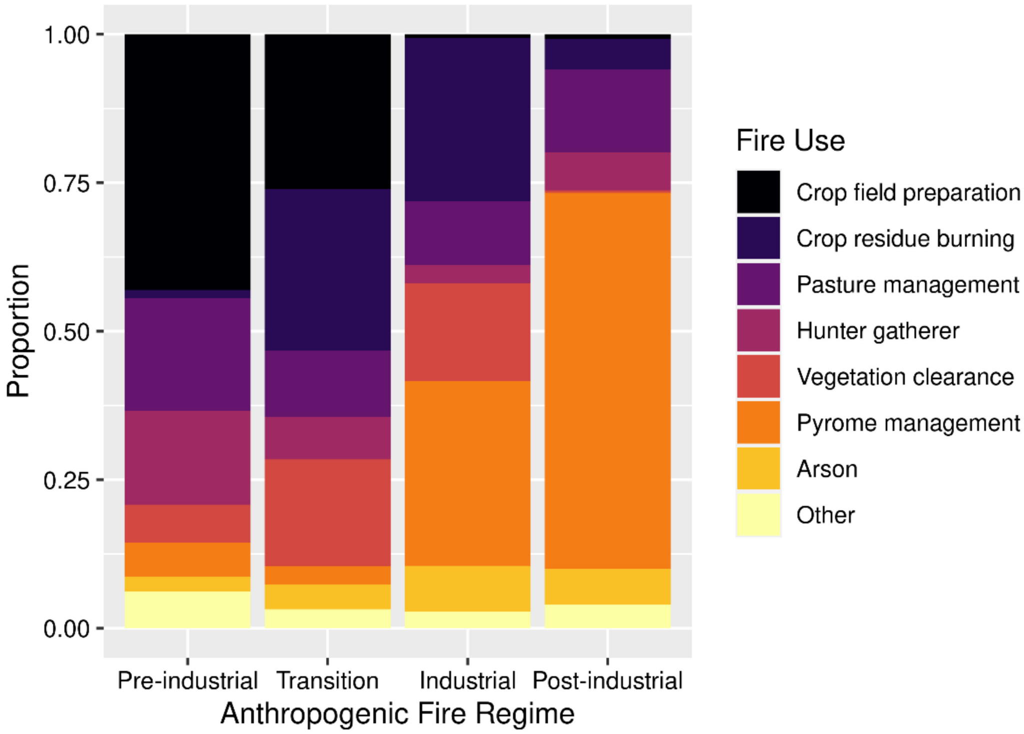

Figure 2. Fire use by Anthropogenic Fire Regime The fire uses are the seven main modes of fire use identified in DAFI (see Table 2). Proportions are based on the number of studies in each fire regime.

Pyrome management activities dominate in North America and Europe, while vegetation clearance is a primary use across much of Brazil, and crop residue burning is dominant across parts of Asia (Figure 1c). Fire is predominantly used in pre-industrial regimes for crop field preparation, hunting/gathering, and pasture management (Figure 2). Transition regimes also have a large proportion of crop field preparation fires but with crop residue burning and vegetation clearance fires as dominant partners. In contrast, crop field preparation fires are not found in industrial or post-industrial regimes, in which pyrome management fires become prominent (particularly for post-industrial).

3.2.2. Physical Characteristics

In general, anthropogenic fire regimes are typified by small but densely-lit fires. When examining case study fire sizes and total burned area we group by fire use into 'cropland' (field preparation and crop residue burning) and 'broadcast' (all other fire uses) fire types. Furthermore, we consider only fires deliberately set by humans and ignore fires that escaped from their intended purpose. Clear differences in the distribution of mean fire size and total burned area are evident, both when disaggregating by anthropogenic fire regime and when considering all fires combined (Figure 3). Combined, cropland fires tend to be smaller than broadcast fires but burned area is generally greater for cropland fires compared to broadcast (highlighting the high frequency of small fires for cropland use). Data in DAFI show that deliberate anthropogenic fires occur (where present) at a median and mean rate of 0.08 and 1.53 km^{-2} $year^{-1}$, respectively. Similarly, fire return intervals are typically short, with median of 3.0 and mean of 6.4 years. Mean fire sizes are distinctly smaller for cropland fires in Pre-Industrial and Transition regimes, but differences are difficult to discern for Industrial and Post-Industrial which have low frequency of cropland fire use. The mean size of broadcast fires is similar for Pre-Industrial and Transition regimes, becoming larger for Industrial and Post-Industrial regimes. Reporting of burned area is less frequent than fire size. The relatively large difference in cropland vs. broadcast burned area for case studies in the Transition regime drives the overall pattern of greater cropland burned area compared to broadcast.

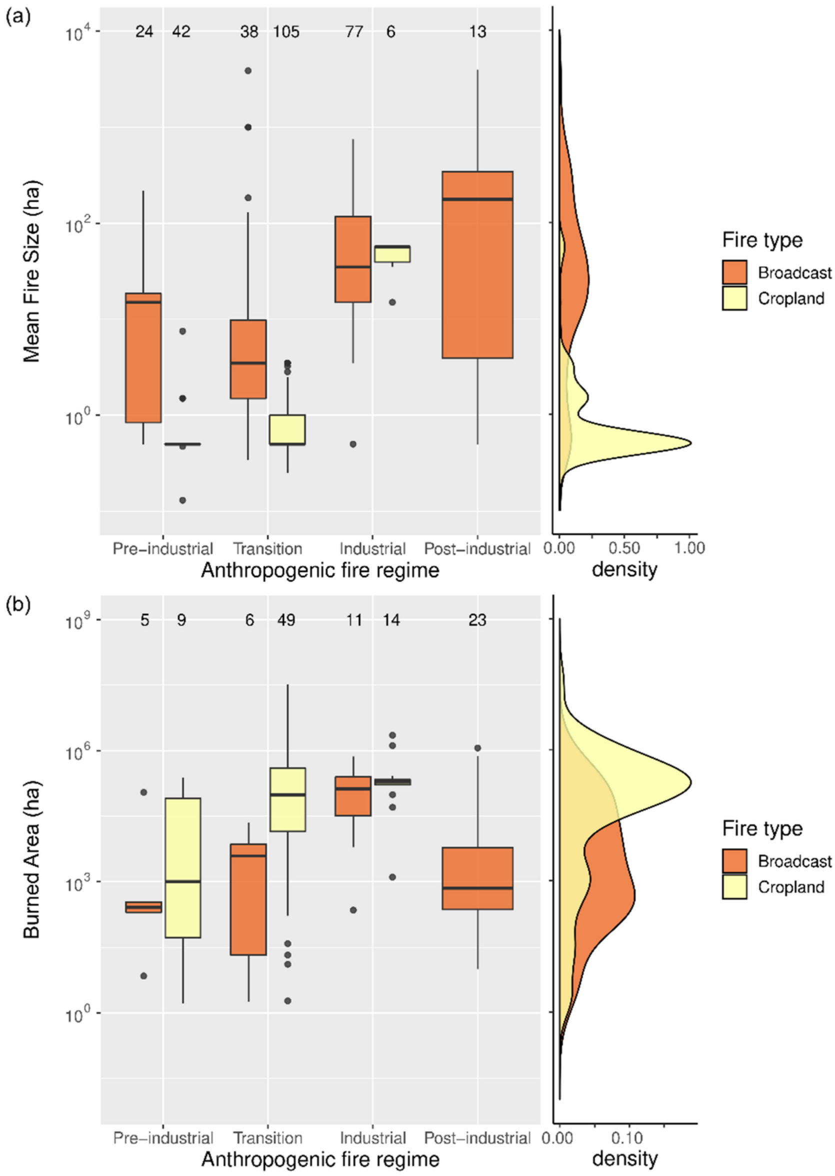

Figure 3. Distributions of (**a**) fire size and (**b**) burned area in DAFI. Data are grouped by Anthropogenic Fire Regime (box plots) and combined in kernel density estimates. Fires are also grouped by fire use; cropland fires are 'field preparation' and 'crop residue burning' uses, with broadcast fires composed of all other uses. Cropland fires are smaller (mode < 1 ha) yet can contribute to larger burned areas than broadcast fires.

Table 2. Seven main modes of fire use identified from meta-study. Proportions of DAFI records are calculated based on unique fire use instances (as case studies can contain multiple fire uses). Mean burned area is as a percentage of the target land cover. Full details on identifying the main modes are presented in Appendix A (Table A1).

Fire Use	DAFI Records (%)	Description	Key Reference	Mean Size (ha)	Mean Burned Area (% LC)	Mean Return Period (yrs)	Escaped (%)
Crop Field Preparation	20.6	Preparing temporary fields for crop planting	[51]	0.8	12.8	9.8	0.06
Crop Residue Burning	17.4	Removing unwanted crop debris post-harvest	[73]	3.9	22.8	1.5	0.01
Pasture Management	12.8	Supporting livestock farming by improving forage or combating pests	[74]	33.9	32.1	3.0	5.01
Hunting–Gathering	6.7	Catching wild animals and fish for meat; harvesting plants and fungi for food, shelter, or medicine	[75]	2.1	9.1	4.3	1.10
Vegetation Clearing	14.0	Permanently clearing primary vegetation for extractive land use (e.g., agriculture)	[76]	9.2	6.6	N/A	0.95
Pyrome Management	18.5	Managing intensity, frequency, timing of fires by altering vegetation characteristics	[57]	357.2	8.9	5.6	0.06
Arson	3.5	Deliberately causing damage to persons or property	[77]	N/A	N/A	N/A	N/A

3.3. Fire Suppression

We find distinct differences in fire suppression between anthropogenic fire regimes (Figure 4). Fire suppression in case studies classed as Pre-Industrial are focused on fire control activities (limited effort and traditional practices) undertaken prior to intentional burning. Where fire prevention measures are taken in Pre-Industrial AFRs, these are overwhelmingly informed by Indigenous and traditional practices such as patch burning in fire-prone environments [27,57,70]. There are very few examples of fire extinction activities for Pre-Industrial case studies. In contrast, all other AFRs have many examples of extinction activities, with relatively fewer case studies using control activities (except for Transition which has many examples of all types of suppression activities).

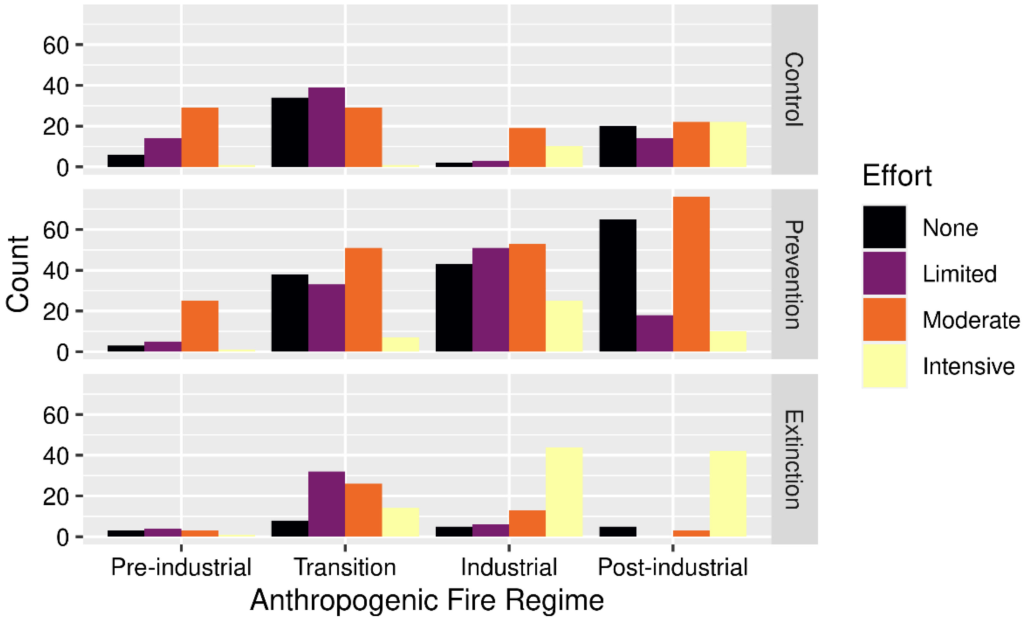

Figure 4. Fire Suppression by Anthropogenic Fire Regime. Counts are of case studies including a given fire suppression action. Effort levels are described in Section 2.2.2.

The Transition regime has the greatest number of case studies with uncontrolled burning; this occurs both due to the purpose of fire use (e.g., for land clearance) but also where community-led mechanisms of fire governance such as communal burning and fire calendars break down under market forces [78–80]. Although the Transition AFR has more examples of extinction activities than the Pre-Industrial regimes, these activities are mostly of limited or moderate effort. Extinction activities for Industrial and Post-Industrial regimes are dominated by intensive efforts. Post-Industrial case studies with intensive extinction are primarily on abandoned croplands and wildland-urban interface areas, whereas case studies with no or moderate/traditional prevention are those utilising prescribed grazing or with pyro-diversity management objectives. Across all suppression types, Industrial and Post-Industrial regimes have a higher proportion of case studies with intensive effort compared to Pre-Industrial and Transition regimes.

3.4. Fire Policy

Instance of policies in DAFI vary by both anthropogenic regime and the rationale driving the policy (Figure 5). For example, incentives are used most frequently when the rationale of the policy is economic, but overall examples of bans are more common (355 examples in case studies versus 273 incentives and 219 restrictions). Bans are most prevalent in the Transition regime but are also relatively common in Pre-Industrial contexts. Furthermore, when the policy rationale is environmental, bans are the dominant policy type across the anthropogenic regimes, except in Post-Industrial contexts where incentives are most used. Restrictions are most prevalent in Industrial and Post-Industrial regimes for Health (and unknown) rationales.

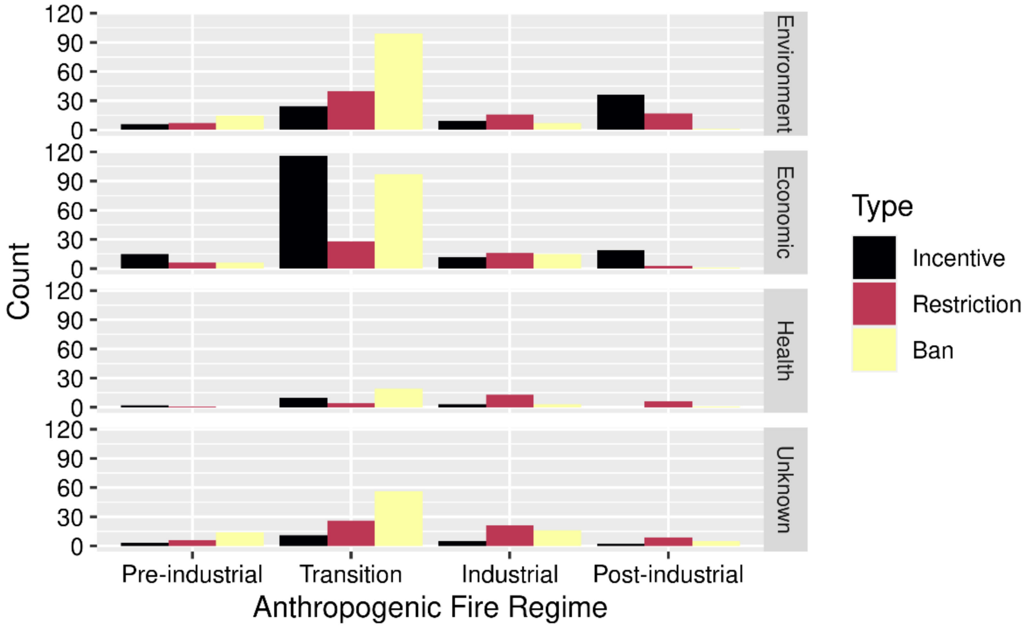

Figure 5. Fire Policy by Anthropogenic Fire Regime. Counts are of case studies including a given fire policy type. Policy rationales are described in Section 2.2.3.

4. Discussion

4.1. Improving the Quality of Anthropogenic Fire Data

Our work confirms that anthropogenic fire use has been studied across a wide array of disciplines, but often only as a function or incidental consequence of another process or system. Conversely, where anthropogenic fire use has been studied explicitly, it has often been in the context of anthropological literature that focuses on Indigenous, traditional, or small-holder practices and primarily reports qualitative data. For example, instances of fire use for hunting and gathering in the database averaged 0.52 quantitative metrics reported compared to 0.92 overall.

This situation may simply reflect that ongoing research is needed to develop trans-disciplinary approaches to fire ecology [29]. However, there are further considerations in the study of Indigenous fire practices that arise from the complex history and politics of anthropogenic fire use and knowledge. Pragmatically, Indigenous and traditional fire practices have often been made illegal by state institutions, particularly under economic development (Figure 5). The result is that if practiced, traditional fire must be used in a clandestine manner (e.g., [81]), which makes open conversations with external researchers inherently challenging and therefore limits data availability. This data availability challenge can be seen most clearly in DAFI for Arson fires, for which metrics are not reported in Table 2. More fundamentally, quantitative measures are not usually the way in which Indigenous and traditional communities understand their fire use and management [82]. Rather, researchers have found participatory methods such as fire calendars, fuzzy cognitive maps and rich pictures to be effective in enabling open dialogue with traditional fire practitioners [83]. There is also a clear danger of researcher extractivism, where knowledge is acquired from Indigenous people and integrated into existing power dynamics, with limited benefit to those communities themselves [84].

With these vital ethical considerations in mind, it remains the case that more consistent reporting of quantitative metrics of fire in studies of Indigenous and traditional practices would be highly beneficial to global modelling efforts. There is substantial variability in which quantitative metrics are reported. For example, we find that in case studies, burned area metrics are reported less frequently than fire size metrics (6.5% of case studies vs. 17.1%). Studies of pre-industrial fire uses such as [74] that provide detailed field-based quantification of anthropogenic fire regimes alongside a nuanced account of the drivers of fire use in the location are exemplary.

There is also a substantial need for detailed studies of industrial fire uses that link fire regime observations to land use rationale. Although the advances in remote-sensing-derived fire databases continue apace (e.g., [85,86]), understanding the socio-economic and human behavioural context of the fires represented in these sources is vital for improved global modelling of anthropogenic fire. The need to link social science with remote sensing, to join people and pixels [87], remains. That is, while remote-sensing data can provide invaluable information about physical characteristics of the earth's surface (e.g., burned area), there is an ongoing need to make these data more relevant and useful for understanding and examining economic, political, and social processes that underpin anthropogenic fire use and management (e.g., [88]).

As is common in meta-analysis studies in land system science, a further consideration of data quality is the geographical representativeness of the available (English language) literature. Currently, DAFI does achieve geographic coverage in areas such as the Nile Delta, Northern India and the Congo Basin (Figure 1) in contrast to studies on the drivers of land use change which are currently sparse in these regions [89]. However, data in DAFI remain sparse for Siberia and Central Asia. This is partly because some government statistics across those regions need to be treated with caution [90], and so are not included in DAFI, but also partly because wildfires in the Northern Boreal and Arctic regions of Russia are still a relatively recent emerging environmental hazard on a large scale [91]. Furthermore, the compilation of DAFI primarily used English language sources, and this brings with it an inherent bias towards regions dominated by anglophone research. Efforts to overcome these geographic gaps and biases need to be addressed as DAFI continues to grow.

Although we find geographical coverage is perhaps less of an issue here than in some land use meta-analyses, a particular challenge for the study of fire use is the inclusion of fire-free land users. For example, studies examining or discussing the role of land abandonment in fire regimes (e.g., [47,92]) met the criteria for inclusion in DAFI by featuring at least one anthropogenic fire behaviour. However, studies where fire-free land use dominated and where no indirect impacts on fire regimes were reported did not meet criteria for inclusion. Two measures were taken to mitigate against this issue when compiling DAFI. First, fire absence was recorded where it was explicitly noted as such in a source (15% of all fire use records). Second, all land users noted by a study were included in DAFI, regardless of whether they were noted as contributing to the fire regime. Importantly, a process of weighting case studies can allow sampling biases to be corrected in analysis and modelling. By weighting data in DAFI so that their distribution corresponded with the global distributions of the Human Development Index (a proxy for societal development) and potential evapotranspiration (a proxy for the biophysical drivers of fire), DAFI has been found to be a robust source for global gridded spatial modelling [93].

4.2. Modelling and Observing Anthropogenic Fire Regimes

Previous studies have identified two underlying issues that lead to the noted deficiency in representation of anthropogenic fire impacts in DGVMs. The first is a lack of understanding of process that enables truly prognostic modelling [20], and the second is a lack of data from which to derive improved parameterisations [18]. By placing anthropogenic fire use, suppression and policy in their land use context, the data in DAFI directly addresses both issues. Our seven main modes of anthropogenic fire use and associated quantitative characteristics provide a logical starting point for improved global modelling.

A specific issue is the need for improved understanding of regional differences in why and when people burn on croplands [18]. Data recorded in DAFI can offer insights here. For example, mapping cropland burning practices with data on seasonal timing of burns suggests spatial differentiation (Figure 6). Case studies of crop field preparation are prevalent in South America and sub-Saharan Africa where shifting cultivation remains a widespread land management system [94]. Conversely, crop residue burning is prevalent in areas of intensive (or intensifying) agriculture in developing countries—principally northern India, north-eastern China and the Nile Delta region as well as eastern Europe (Figure 6). In these regions, mechanisation enables high yields that mean farmers produce greatly more crop residues than can be productively used [53,95]. Whereas in more developed countries environmental or public health legislation is in place to restrict the burning of these residues [96,97] this often does not exist or is not enforced in less developed regions [98,99]. This transition from shifting cultivation fire use for field preparation to residue burning in intensifying systems is perhaps most starkly illustrated in northern India: northern hemisphere winter crop field preparation dominates in the northeast whilst two-season (spring–autumn) crop residue burning characterises the northwest (Figure 6).

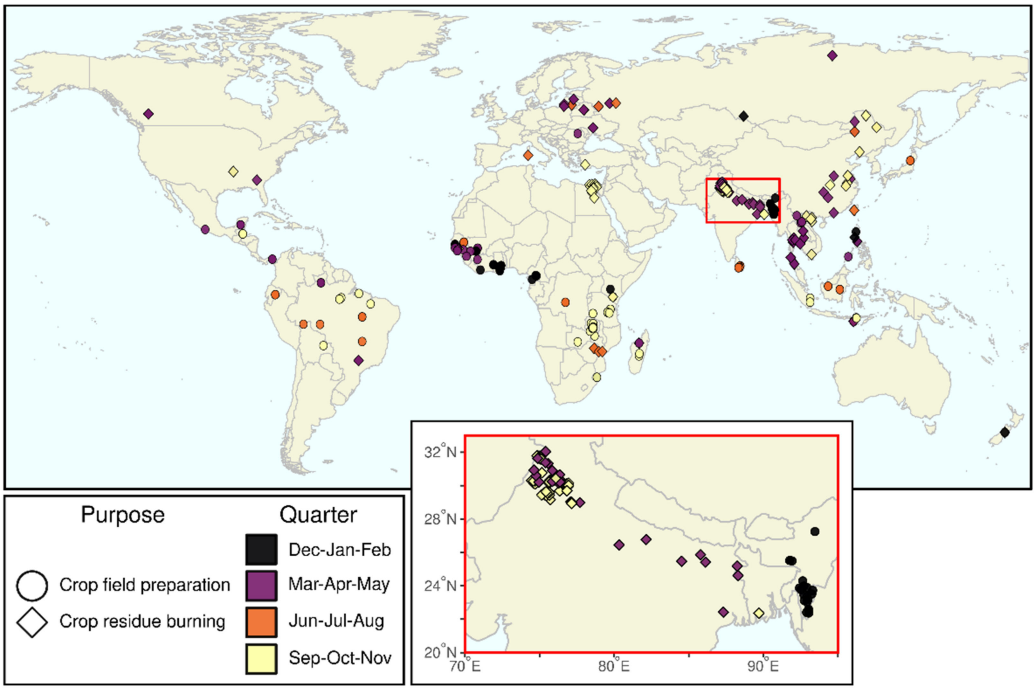

Figure 6. Spatial distribution of DAFI 'fire season start' data for cropland fire practices. Start months are grouped by year quarter.

Here, we simply use data from the 'fire season start' field of DAFI, but much more detailed analysis could be undertaken depending on the understanding demanded for a particular application (e.g., incorporating 'fire season end' data to understand length of burning windows). As with other quantitative metrics in DAFI, contextual understanding and caution is needed; fire timing data in DAFI are often estimates or best approximations as the actual timing of burning can be variable from year-to-year (e.g., with farmers waiting to burn immediately prior to the arrival of the monsoon, which can vary inter-annually). However, further detailed examination of these data will provide insights on the regional differences in fire use and management that will be useful for global modelling.

The performance of fire-enabled DGVMs is commonly assessed by comparing model outputs to burned area estimates from MODIS-derived satellite sensor products (e.g., [19]). However, these burned area products are known to have difficulty detecting small fires [100], with a minimum detected burned area of 21 ha [101]. We find that 60% of records in DAFI for mean size of deliberately started fires are <21 ha, suggesting many anthropogenic fires will not be detected by long-established MODIS-derived products. Use of Sentinel-2 derived fire data (at 0.04 ha spatial resolution) has shown how MODIS-derived products may underestimate burned area by up to 80% across Africa and that fires <100 ha are critically important for characterizing landscape fire on a global scale [102]. Our results from DAFI support this; 79% of mean fire size records for deliberately started fires are <100 ha, and Crop fires in Pre-Industrial and Transition regimes are generally smaller compared to fires ignited to burn across landscapes more broadly (Figure 3a).

We also find a discrepancy between the median density for deliberate anthropogenic fires in DAFI of 0.08 (Section 3.2.2) and the median value suggested by the MODIS-derived global fire atlas of less than 0.01 fires km^{-2} year^{-1} [44]. The mean density in DAFI of 1.53 km^{-2} year^{-1} indicates a skewed distribution and the DAFI-MODIS discrepancy is most acute in regions of intensive crop residue burning in tightly packed fields. For example, in the Mekong Delta, there are typically three harvests a year, on fields averaging 0.9 ha in size [103,104]. Applying a conservative assumption that a third of fields are at least partially burned at each harvest, suggests 111 fires per km^2 of cropland. Allowing space for unfarmed spaces such as hedges, marginal lands, etc. this is consistent with the up to 100 fires km^{-2} year^{-1} implied by [103]. Therefore, although previous Landsat studies suggest that MODIS-derived data underestimated the number of fires in agricultural landscapes by a factor of 10 [105], data in DAFI suggest the underestimation may be an order of magnitude larger than this at the upper end in other locations. Continued advances in remote sensing of small fires will be beneficial to ensure that outputs of DGVMs with improved representation of anthropogenic fire are appropriately compared to empirical observations that capture the full picture of human fire activity.

4.3. Categorising Anthropogenic Fire Uses and Regimes

We find distinct signatures of our anthropogenic fire regimes in terms of fire size, area and suppression effort (Figures 3 and 4). The seven main modes of fire use we identify closely correspond to the anthropogenic fire regimes in the typology of [42], but with the addition of residue burning and with pastoralism and hunting–gathering split into separate categories. Crop residue fires were split from shifting cultivation fires (field preparation) owing to their differing purpose and function within the land system (e.g., [2,95]). Similarly, fires for pasture management and hunting–gathering were split due to their differing land use goals (e.g., [52,75]). In both cases we subsequently found differences in quantitative metrics for the fire uses (Table 2). In particular, hunting–gathering fire sizes vary more than pasture management fires, with sizes ranging from 1.4 ha to 8345.0 ha for the former compared to 4.4 ha to 244.8 ha for the latter.

Our approach to identifying the seven fire uses was driven by theory and existing work (Section 2.1), but also with process-based modelling in mind. Alternatively, we might have taken a more data-driven approach, collating quantitative data and then applying clustering methods to identify coherent categories of fire use solely through quantitative variables. However, a clustering approach was prevented here by the sparse and inconsistent reporting of quantitative variables in studies used to compile DAFI. Furthermore, our intended use of DAFI to aid modelling through improved representation of human agency (e.g., [93]) meant that a process-led definition of categories was preferable to avoid 'chaotic conceptions' that artificially "lump together the unrelated and the inessential" [106]. Data-driven approaches may be more suitable for other research objectives and as further data are added to DAFI these methods will become more practicable. Similarly, our definition of four anthropogenic fire regimes—Pre-Industrial, Transition, Industrial, Post-Industrial—was rooted in existing literature but produces distinct quantitative signatures when used to analyse case study data in DAFI. Case studies included in DAFI were assigned to an anthropogenic fire regime based on our reading of the system being studied, but the quantitative signatures became apparent subsequently. In attributing a location as belonging to a given AFR, we do not intend to make the ecological fallacy of implying that all actors in the region have identical attitudes or practices. However, if human agency and behaviour are to be represented in large-scale models like DGVMs, then approaches that classify 'types' of human activity are needed [33].

In comparison to previous 'top-down' classifications of human–fire interactions, the quantitative signature of anthropogenic fire regimes found in these results are perhaps closest to the 'pyromes' approach of [21], who suggest that the anthropogenic footprint is principally to push diverse natural fire regimes towards a homogenous picture of many, cool and small fires. However, exceptions to this are found in widespread prescribed burning for biodiversity conservation (e.g., [107]), large-scale deforestation for commercial agriculture (e.g., [76]), as well as the potential for blanket fire suppression to contribute to the occurrence of megafires (e.g., [108]). This points to the underlying difficulty of categorising anthropogenic fire impacts without seeking to account for the multiple interacting social and ecological drivers that combine to produce observed fire patterns. For example, in the case of isolated rural communities responding to economic development, the combination of persistent fire use, diminishing fire knowledge and fracturing of communities under market forces and population growth can together lead to phases of chaotic and uncontrolled fire use [71,79,109].

The existence of quantitative differences between our anthropogenic fire regimes highlights that modelling of anthropogenic fire would do well to avoid the fallacy that drivers of all human fires are identical and universal. Although they are readily available globally, simple metrics such as population density and GDP will likely be inadequate to capture differences in how people use and manage fire. However, combining these metrics with understanding of how, where and why human use and management of fire varies around the world should lead to improved representation in global models (e.g., [93]).

5. Conclusions

The new database of anthropogenic fire impacts (DAFI) presented here represents the first global synthesis of quantitative data on human–fire interactions across all types of land use system. Through analysis of DAFI we have identified seven main modes of human fire use that together account for 93% of database records. We describe the underlying rationales of these seven modes, map their spatial distribution and summarise their quantitative characteristics. In doing so we provide new understanding that can become the basis of improved representation of anthropogenic fire in global process-based models. Additionally, our work reveals the global quantitative signatures of anthropogenic fire regimes: at least 60% of deliberate anthropogenic fires burn less than the 21 ha at which MODIS can detect fires (against which many fire-enabled DGVMs have previously been parameterized).

Alongside these advances, DAFI highlights the ongoing challenges for research of anthropogenic fire use and management. Perhaps foremost among these is the continued need for a transdisciplinary approach to fire science that links fieldwork documenting human fire use and management practices with quantitative analysis of the resulting fire regime. This kind of local, fine-scale work is invaluable for global, broad-scale understanding, but also poses important ethical questions in the case of Indigenous fire practices and raises pragmatic issues in the case of clandestine or illicit fire use. Spatially, the clearest data gap is in Siberia. This must be considered an important research priority given the increasing rate of fire in this region. Despite caveats such as these, understanding and modelling human fire use and management globally can be improved by analysis and synthesis of local data like those in DAFI, potentially in combination with broad-scale and remotely sensed data. We encourage readers to work with DAFI for their own analyses and modelling.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire5040087/s1, Supplementary Material: Main modes of fire use identified in the Database of Anthropogenic Fire Impacts. References [110–133] are cited in the supplementary materials.

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Appendix A

Table A1. Systematic search terms used for the meta-study of global anthropogenic fire use. Although all search terms are assigned to one AFR-land use combination, several (e.g., residue burning, and biodiversity conservation) are applicable across divisions.

AFR	Land Use		
	Forestry	**Livestock**	**Cropland**
Pre-Industrial	Traditional fire knowledge; traditional fire use; traditional ecological knowledge AND fire; Indigenous fire use; Aboriginal burning; Aboriginal fire use; hunting AND fire; patch mosaic burning	Migratory pastoralism AND fire; pastoralist AND fire; transhumant herder AND fire; nomadic herder AND fire	Shifting cultivation AND fire; swidden; "slash and burn" AND fire; Citamene AND fire; "slash and mulch"
Transition	Charcoal making; charcoal production; fire use timber harvesting; logging fires; fire illegal forestry; fire tropical timber extraction Fire-free agroforestry; agroforestry fire use	Rangeland burning; rangeland AND prescribed fire; pasture burning; pasture renewal fire; pasture fire; escaped pasture fire; rangeland management fire; pasture AND deforestation	Straw use AND fire; straw management AND fire; crop residue disposal AND fire; agricultural fires, field burning, agricultural burning, stubble burning; crop residue burning; haze AND agricultural fire; air quality AND agricultural fire; air pollution AND agricultural fire; veld fire; sugar cane burning; pre-harvest sugar cane burning; rice straw burning
Industrial	Forest management AND fire; salvage logging fire; prescribed burning AND forestry; fuel load management; fuel load management AND fire; forest fuel load management; stand thinning AND forestry	Woody encroachment AND fire; rangeland AND fire reintroduction; livestock AND fire management; patch-burning AND livestock	Deforestation AND fire; deforestation AND wildfire; land clearance AND fire; agricultural land clearance AND fire; fire use deforestation
Post-Industrial	Wildland urban interface; wildland urban interface AND fire; wildland urban interface AND fire management; fire paradox; wildland urban interface AND fire paradox; wildland urban interface AND fire suppression; tourist AND accidental AND fire; Pyrodiversity; prescribed burn; pyrodiversity AND management; conservation AND fire; conservation AND prescribed fire; diversity conservation AND prescribed fire	Grazing AND fire management; prescribed grazing; prescribed grazing AND fire management	Land abandonment AND fire; agricultural abandonment AND fire; land abandonment AND fuel load

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