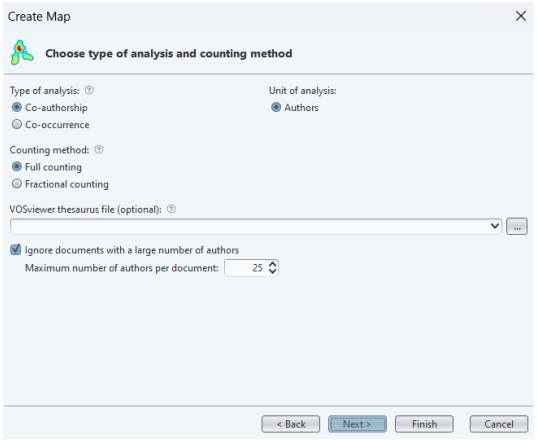
Co-Authorship Network in Fire Spotting Research: Mapping Collaborative Contributions

Co-authorship analysis using full counting identified 265 authors with at least one publication. The network visualizes collaborative links, highlighting key contributors and research partnerships in the field.



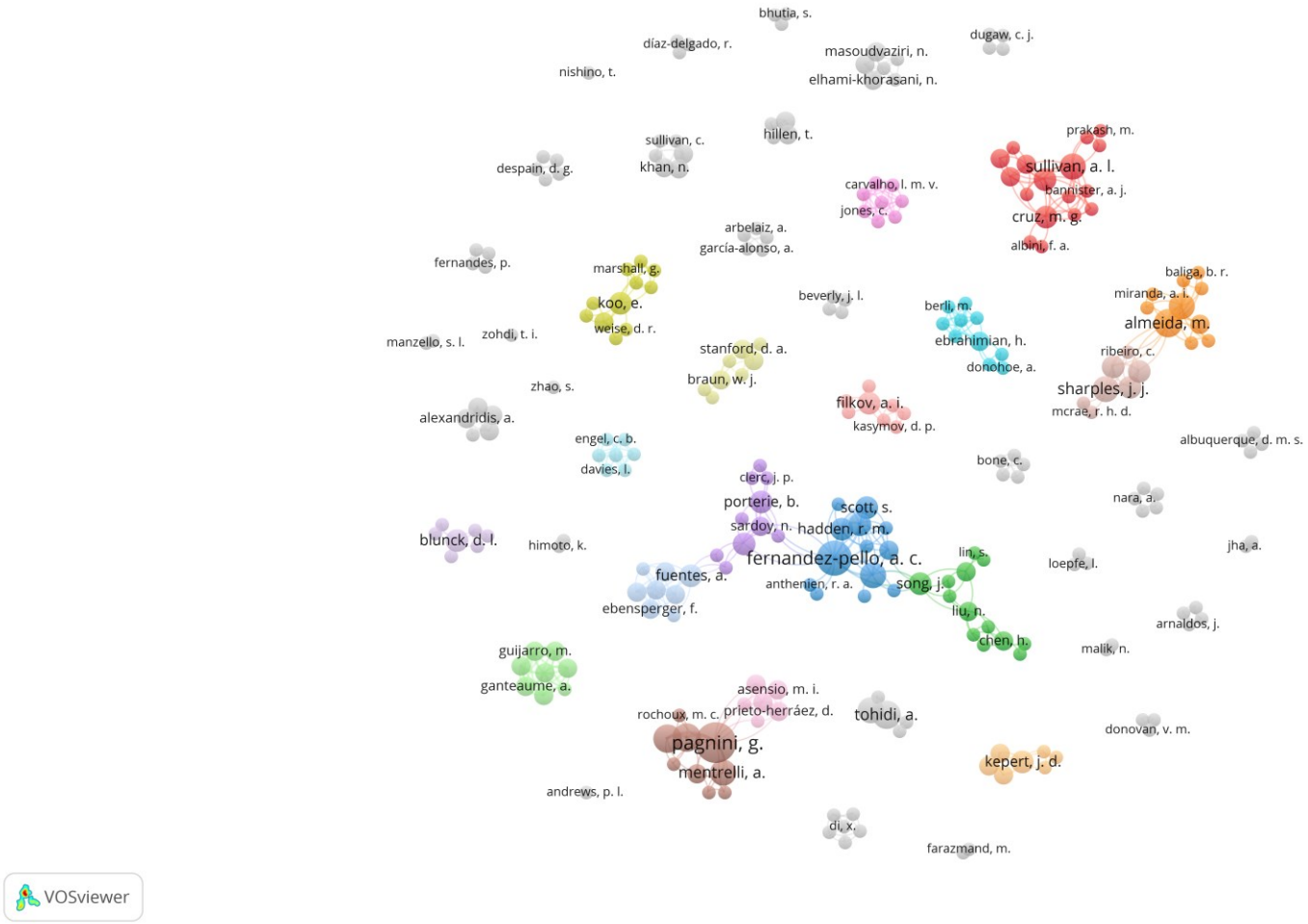


Figure S1. Co-authorship network visualization based on bibliographic data.

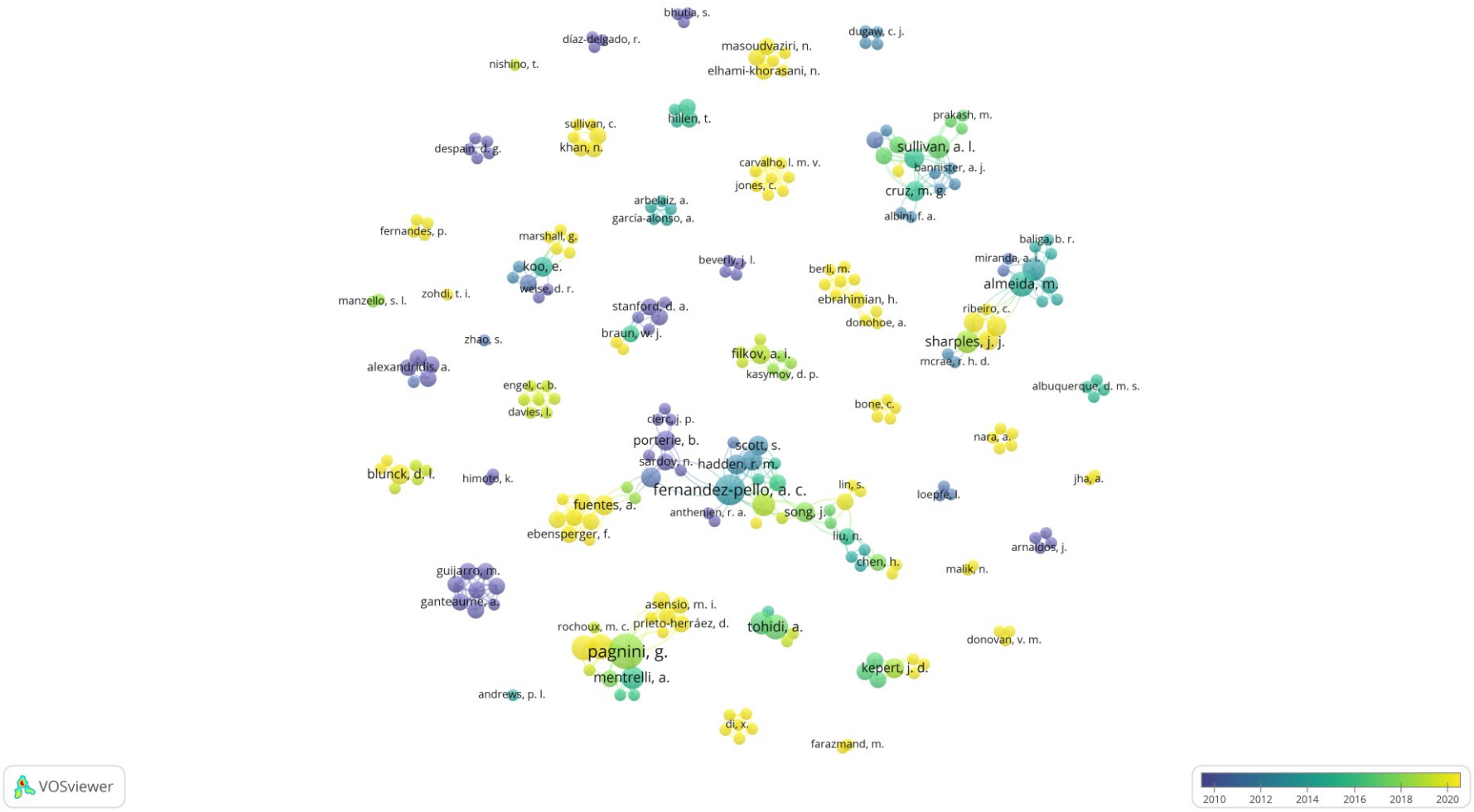


Figure S2. Co-authorship overlay visualization based on bibliographic data.



Figure S3. Co-authorship density visualization (cluster density) based on bibliographic data.

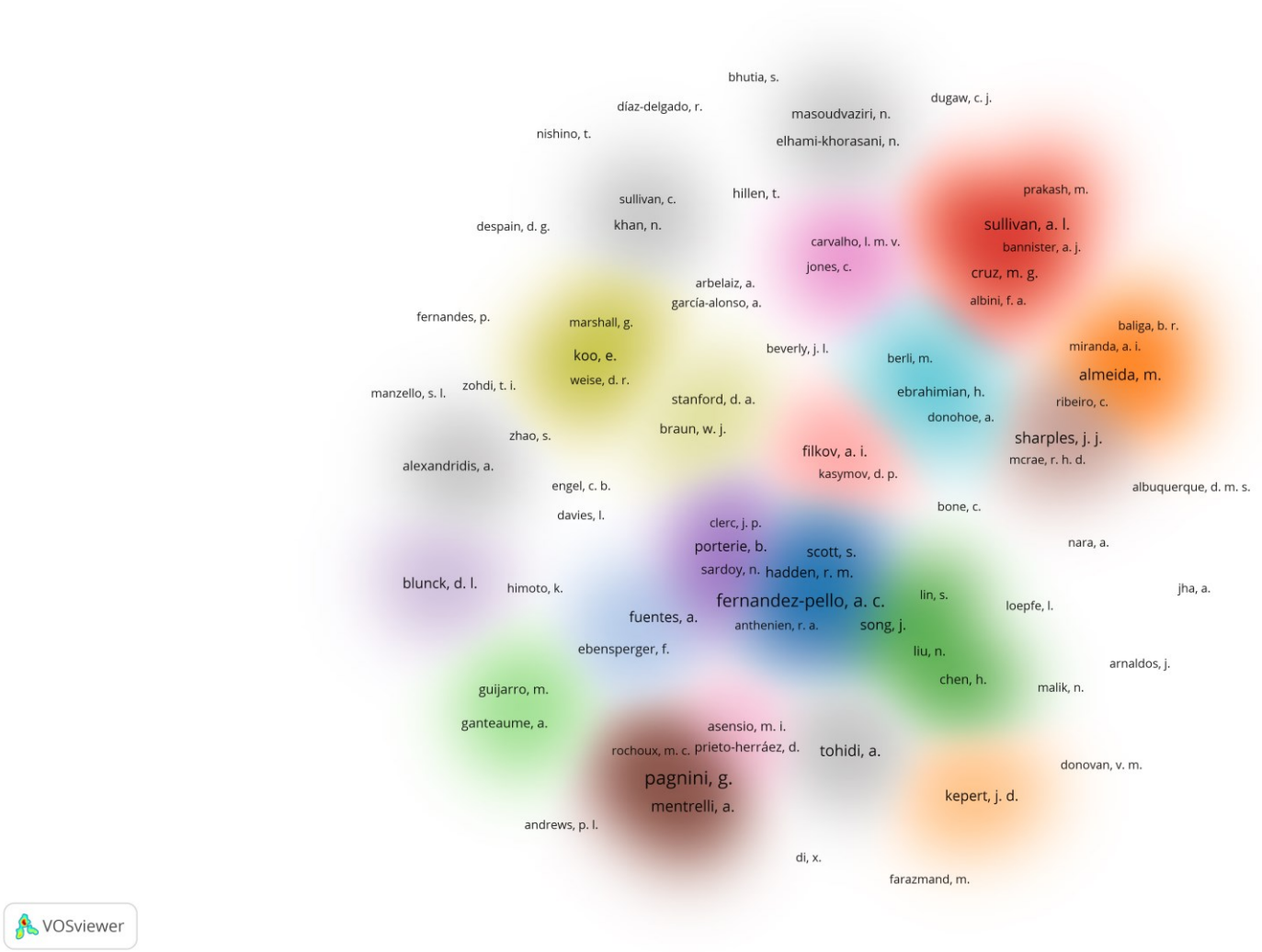


Figure S4. Co-authorship density visualization (cluster density) based on bibliographic data.

Keyword Co-Occurrence Analysis: Mapping Research Themes in Fire Spotting Studies

Keyword co-occurrence analysis was conducted using bibliographic data from 102 documents, employing the full counting method with a minimum threshold of one occurrence, which resulted in 326 keywords. Of these, 262 formed the largest connected network. The total link strength for each keyword was calculated to determine the strongest associations.

Visualization adjustments were made in VOSviewer to optimize the keyword co-occurrence network. The normalization method used was association strength (default setting). In the layout settings, Attraction was set to 2 and Repulsion to -1. The clustering resolution was adjusted to 0.6, resulting in a reduction from 35 to 28 clusters.

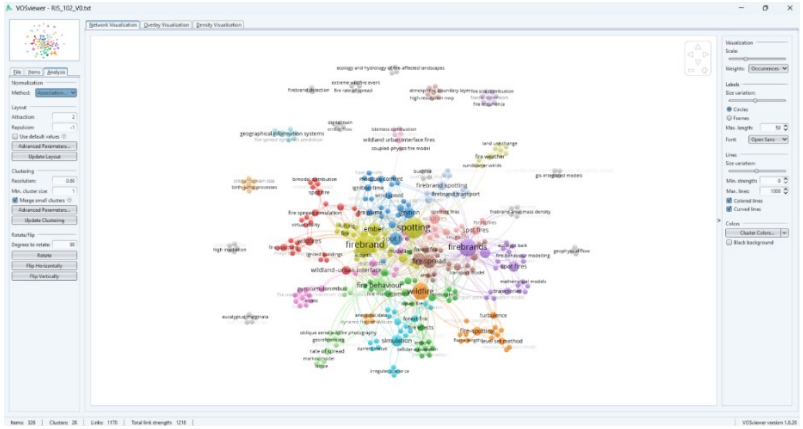


Table 17. Thematic classification of clusters based on keyword co-occurrence analysis.

Cluster	Theme	Key keywords
Cluster 1	Urban Fire Spread and Firebrand Dynamics	bimodal distribution, critical wind speed, external flame, extinction, extinguishment support, fire spotting, fire spread simulation, firebrand aerodynamics, firebrand shower, ignited buildings, ignition by hot particles, image processing, particle tracking, risk assessment, smouldering, spot fire, spotting fires, stochastic model, stochastic simulation, urban fire, urban fires, virtual reality, wildland–urban interface, wildfires, wind tunnel experiments, zone model
Cluster 2	Fire Spotting Dynamics and WUI Protection Strategies	atmospheric, cellular automaton, community, convection, crown fire, defensible space, embyr, fire effects, fire management, fire model, firesmart, firewise, fuel, fuel moisture, interactions, landscape model, modeling, patch formation, pattern, radiation, spotting distance, spotting distribution, surface fire, transport equations, wildfire behaviour, yellowstone national park

Cluster 3	Extreme Fire Behavior and Ignition Dynamics	canopy-top height, critical heat flux, crowning, extreme fire behaviour, fire plume, flame height, heat transfer, hot particle, hot-spot ignition, ignition, ignition time, larix gmelinii, line scan, logistic model, moisture content, packing ratio, pine needles, spot fire, spotting fire, thermal radiation, wildland fuel, wind speed, wui fire
Cluster 4	Fire Spotting and Physics-Based Fire Modeling	acoustic, boreal, buoyant plume, burning embers, dimensional analysis, ember, fds, fire, firebrand, flammability parameters, ground-level distribution, ignition probability, lofting, physics-based modeling, plume, spectrogram, spotting, thermal-degradation, trajectory, wildfire, wildland–urban interface, wind
Cluster 5	Ember Dynamics and Fire Spread Modeling	ember transport, embers, eucalypt bark, fire-behaviour modelling, firebrands, forest fires, fuelbreaks, horizontal distance travelled, lagrangian particle transport model, large outdoor fires, large-eddy simulation, mathematical models, oscillations, pine cone, pine scale, post-fire investigation, rotations, spot fires, total falling time, trajectories, urban fire
Cluster 6	Stochastic Fire Spread and Simulation Models	current status, disturbance, forest fire, geographic information (gis), irregular coarse ca, les, long-range spread, numerical model, openfoam, percolation, Poisson process, right censoring, short-range spread, simulation, small world network, stochastic modelling, terrain analysis system (tas), urban mass fire-spread, wildfire modeling, wind tunnel
Cluster 7	Empirical and Simulation-Based Wildfire Modeling	anecdotal data, atmospheric stability, direct data, discrete event system specification, dynamic fire behaviours, fire simulators, fire-spotting, fireline intensity, flame length, ForeFire, indirect data, level set method, random phenomena, reaction-diffusion model, Rothermel model, terrain slope, turbulence, wildland fire propagation, wildland fire simulation, wildfire
Cluster 8	Stochastic Fire Risk Modeling	amicus, decision support system, experimental validation, fire spread, forest fire, gaussian process, generalized polynomial, monte-carlo simulation, nonlinear regression, post-earthquake fire, rod-like debris, sensitivity analysis, size and mass distribution, software, transport model, urban conflagration, wildland fire, wildland-urban interface
Cluster 9	Fire Behavior in Forest and Atmospheric Conditions	access, access-fire, coupled fire–atmosphere, critical conditions, crown fire, deffm, dry eucalypt forest fire, eucalyptus, experiment, fire meteorology, ground fire, megafire, modelling, pyroc, pyrocumulonimbus, surface fire, vesta, waroona fire
Cluster 10	Fuel Influence on Fire Spread and Spotting	bushfires, douglas-fir, eucalypt forests, fire prediction, fire simulation, forest fires, forward spread rate, fuel bed ignition, generation, ponderosa pine, sagebrush, spot fires, spotting fires, wildfires, wildland urban interface
Cluster 11	Spatial Fire Behavior Modeling	fire behaviour, georeferencing, lattice, markov model, maximum spot fire distance, monophotogrammetry, oblique aerial wildfire photography, rate of spread, remote sensing, spatial model, stochastic fire spread, torching, torching trees, wildfire modeling, wsl monoplotting tool
Cluster 12	Firebrand Generation and Transport	cooperative ignition, firebrand accumulation, firebrand generator, firebrand spotting, firebrand transport, large deviation theory, monte carlo method, rare event simulation, smolder, spot ignition, wildland-urban interface
Cluster 13	Fire Regime and Landscape Dynamics	farsite, fire suppression, fire weather, fire regime, land use change, landscape dynamics, model, sundowner winds, vegetation growth
Cluster 14	Fire Occurrence and Spatial Patterns	fire occurrence, fire recurrence, fire size distribution, fractal dimension, land cover, lorenz curves, post fire, residual vegetation islands
Cluster 15	Complex Systems and Wildfire Dynamics	cellular automata, complex systems, fire spread dynamics, forest wildfires, geographical information, heterogeneous landscapes, mountainous landscapes, spetses island
Cluster 16	Mathematical Models of Wildfire Spread and Spotting	birth-jump processes, critical domain size, diffusion limit, integro-differential equation, minimal wave speed, reaction-diffusion equation, wildfire spotting
Cluster 17	Atmospheric and Weather Modeling for Wildfires	atmospheric boundary layer, black saturday bushfires, high-resolution nwp, mesoscale modelling, shallow convection, stable layer, wind-direction variability
Cluster 18	Fire Physics and Ignition Processes	biomass combustion, coupled-physics fire model, smouldering ignition, spot fire ignition, wildland fires, wildland urban interface
Cluster 19	Extreme Wildfire Events and Fire Spread	extreme wildfire event, fire rate of spread, geovisualization, thermal imagery, wildland fire

Cluster 20	Fuel Hazard and High-Intensity Fire	eucalyptus marginata, fuel hazard ratings, high-intensity experiments, project ember, spotfires
Cluster 21	Fire Ignition Limits and Simulation	high irradiation, ignition limit, numerical simulation, smoldering fire, spotting fire
Cluster 22	Machine Learning for Firebrand Characteristics and WUI Fire Risk	firebrand areal mass density, firebrand areal number density, k-nearest neighbors, machine learning, wildland–urban interface
Cluster 23	Digital Twin and Fire Propagation	digital-twin, ember flow, fire-propagation, machine learning algorithms
Cluster 24	Ecology and Physics of Wildfire	ecology and hydrology of fire-affected landscapes, physics of wildfire behavior, wildfire effects on soil, wildfire models
Cluster 25	Firebrand Aerodynamics in Bushfire	bushfire, coefficient of drag, surface density, terminal velocity
Cluster 26	Stochastic Wildfire Propagation Models	geophysical flow, randomized level set method, reaction-diffusion equation, wildland fire propagation models
Cluster 27	Wildfire Spread Modeling and GIS Integration	gis-integrated flow model, numerical methods for complex simulation model, simplified physical model, wildfire spread model
Cluster 28	Firebrand Detection and Tracking	firebrand detection, firebrand tracking, wildland and structural firebrands

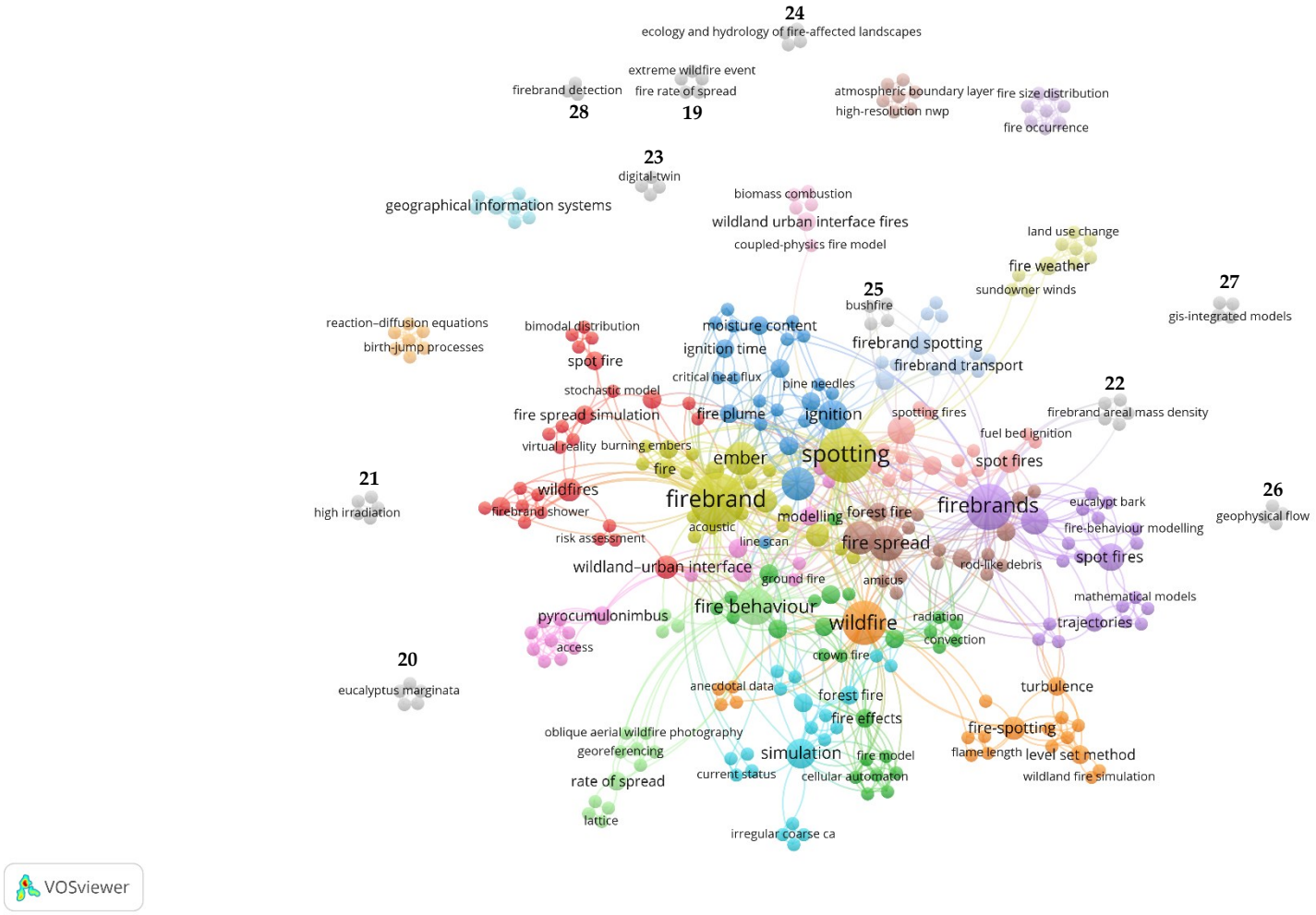


Figure S5. Keyword co-occurrence network visualization based on author keywords.

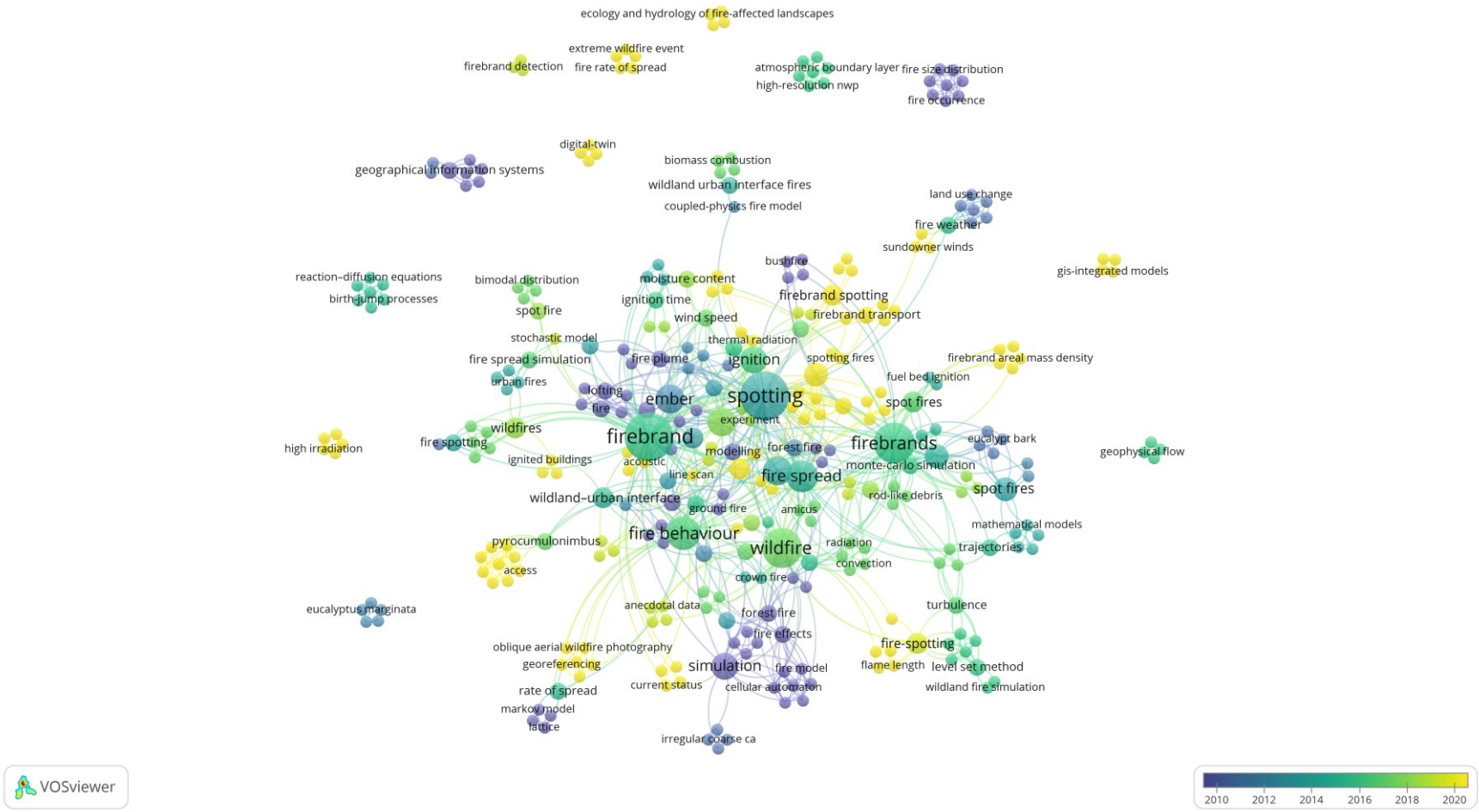


Figure S6. Keyword co-occurrence overlay visualization based on bibliographic data (the author's keywords field).



Figure S7. Keyword co-occurrence density visualization (cluster density) based on bibliographic data (the author's keywords field).

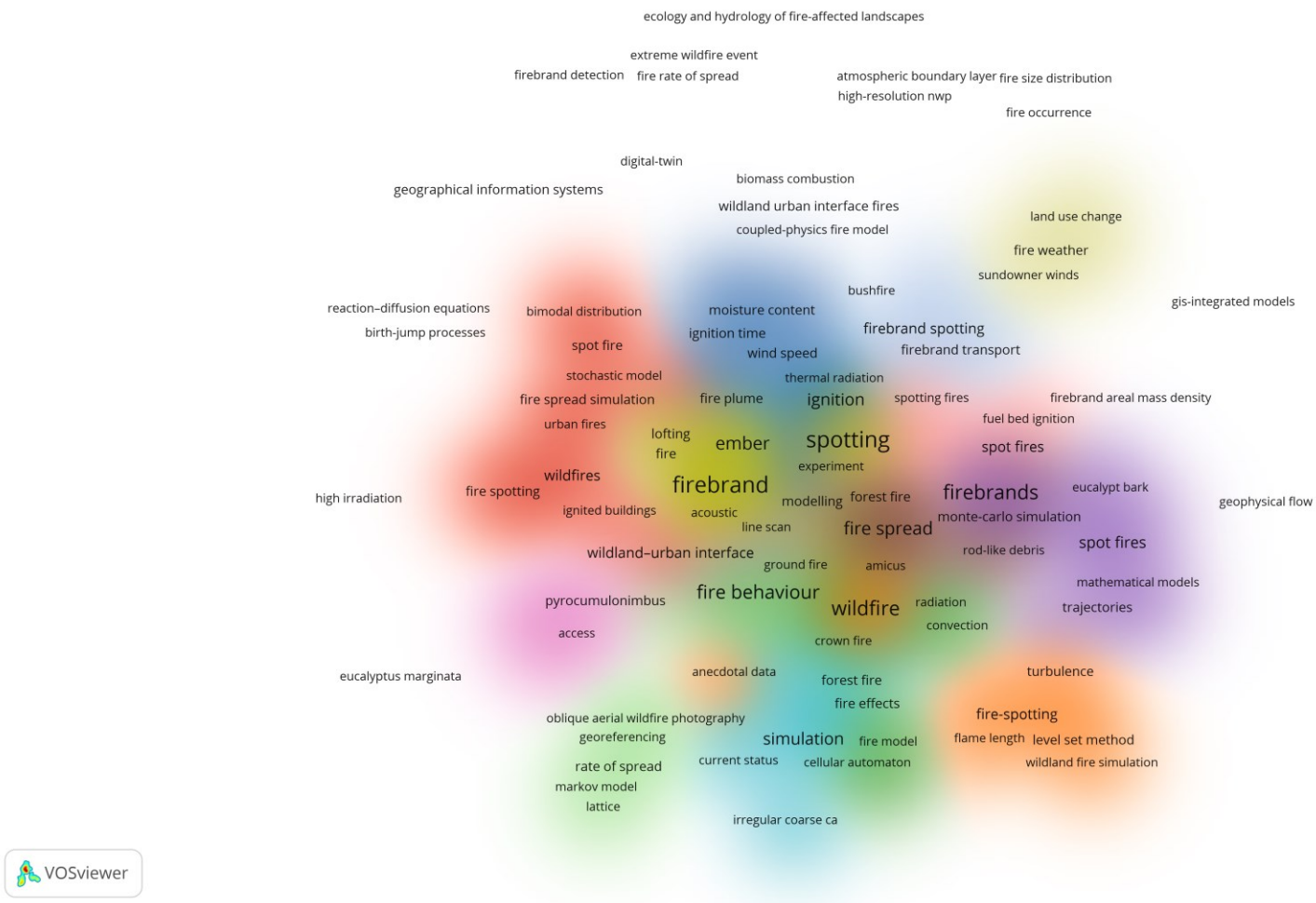


Figure S8. Keyword co-occurrence density visualization (item density) based on bibliographic data (the author's keywords field).

Term Co-Occurrence Analysis and Visualization of Text Data

The term "co-occurrence analysis" was applied to the full titles and abstracts of 102 studies using the Binary Counting method, with a minimum occurrence threshold of two. A total of 342 terms met this threshold, representing 60% of the most relevant terms. Visualization parameters were optimized in VOSviewer: normalization used association strength (default), layout settings were set to Attraction = 2 and Repulsion = 0, and the clustering resolution was set to 1.2, resulting in 13 distinct clusters.

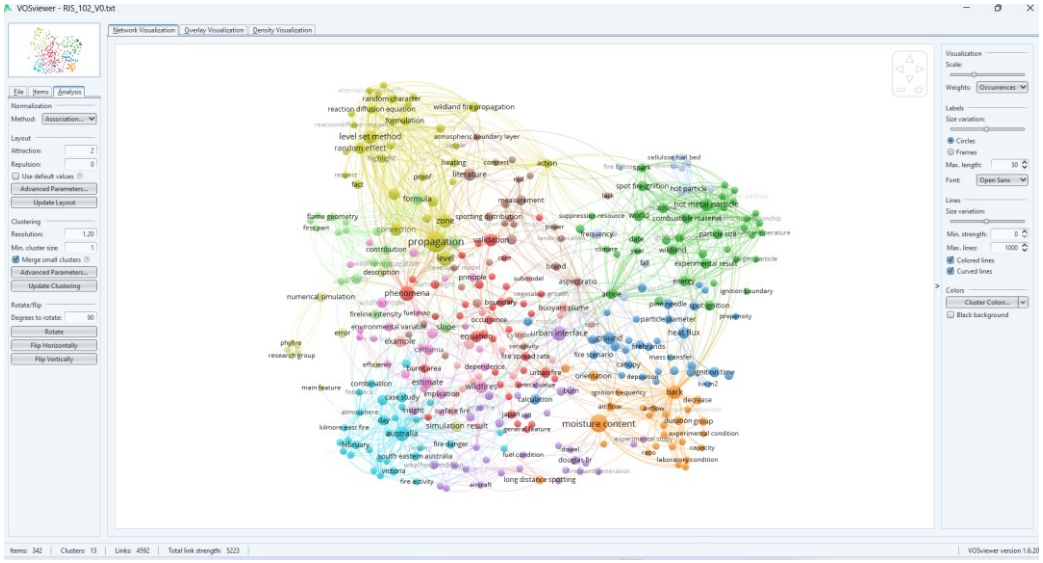


Table 18. Thematic classification of clusters from term co-occurrence analysis.

Cluster	Theme	Key Terms
Cluster 1	Urban Fire Spread, WUI, and Model Validation	account, arrangement, boundary, burnt area, concentration, core, equation, experience, fire occurrence, fire science, fire spread rate, firefighting operation, flame height, general feature, Japan, model evaluation, model verification, new fire ignition, new model, North America, occurrence, period, phenomena, place, secondary fire, spatial pattern, urban area, urban fire, urban fire spread, user, utility, validation, vegetation growth, wildland urban interface

Cluster 2	Ignition Process and Anthropogenic Firebrand Source	article, climate, combustible material, date, energy, experimental result, first step, hot metal particle, hyperbolic relationship, ignition boundary, ignition mechanism, ignition process, important fire ignition point, important source, larger particle, lower temperature, machine, manager, metal particle, numerous case, particle size, power line, smaller particle, smoldering, spark, spot fire ignition, spot ignition, spotting ignition, stainless steel, subject, suppression resource, topic, urban interface fire, urban spot fire, welding, wildland, world, year
Cluster 3	Theoretical and Experimental Modeling of Ignition Thresholds	calculation, canopy, deposition, disk, electric heater, experimental measurement, fire scenario, firebrands, first time, flaming, flight time, forest fuel, ground, heat flux, idealized firebrand, ignition delay time, ignition time, incident heat flux, km2, mass loss, mass transfer, numerical study, particle diameter, pine needle, propensity, pyrolysis, single firebrand, theoretical analysis, theoretical model, thermal degradation, thermal ignition theory, thickness, top
Cluster 4	Mathematical Modeling of Fire Spread with Random Effects	action, alternative approach, concept, contour, convection, evolution equation, fact, fire spotting phenomena, formulation, heating, leeward sector, level, level set method, performance, probability density function, proof, propagation, random character, random effect, random front, random nature, reaction diffusion equation, reaction diffusion equation, respect, simple, simplification, turbulence, turbulent hot air transport, wildland fire propagation, zone
Cluster 5	Firebrand Generation Process and Landscape-scale Wildfire	active wildfire, adequate manner, aircraft, burn, cell, cellular automata, chance, critical value, current model, Douglas fir, dowel, environmental condition, experimental study, firebrand generation, firebrand generation rate, firebrand production, fuel condition, fuel load, heterogeneous landscape, humidity, large fire, lattice, ponderosa pine, potential threat, pseudotsuga menziesii, quantification, river, shrub, source fire, urban interface fire, weather condition
Cluster 6	Regional Case Studies and Atmospheric-Fire Modeling	atmosphere, australia, australian community climate, black saturday, bushfire, case study, combination, day, earth system simulator, eucalypt forest, extreme fire behaviour, fatality, feedback, fire activity, fire danger, fire grid, grid spacing, high fire danger, horizontal grid spacing, january, kilmore east fire, local topography, long range spotting, model output, near surface condition, pyrocumulonimbus cloud, short distance, south eastern australia, suite, UK Met Office Unified Model
Cluster 7	Aerodynamics and Experimental Ignition	air flow, airflow, bark, capacity, decrease, duration, experimental condition, experimental laboratory, flaming phase, flow velocity, group, ignition frequency, ignition probability, important mechanism, laboratory condition, leaf, long distance spotting, moisture content, orientation, phase, pine cone, ratio, significant effect, southern Europe, trend, weight, wide range
Cluster 8	Firebrand Transport Modeling	aspect ratio, atmospheric boundary layer, brand, contrast, developed model, downwind transport, firebrand shower, firebrand shower scenario, flight distance, half, initial condition, lack, landing location, literature, measurement, model firebrand, power, rod, sensitivity, software, spotting distribution, stochastic model, stochastic modeling, transport model, variety, velocity field
Cluster 9	Wildfire Modeling Gaps and Challenges	california, database, dependence, destructive wildfire, environmental variable, estimate, fire feature, fire front position, fire growth, gap, implication, important factor, limitation, maximum, metric, min, principle, recent year, ros, wildfire model, wildfire science
Cluster 10	Mathematical and Physical Modeling of Wildfire Propagation and Flame Characteristics	average, buoyant plume, cellular automata model, cylinder, example, firebrand trajectory, horizontal distance, important parameter, incorporation, landing pattern, landing pattern, recipient fuel, spot fire development, spot fire distance, stochastic simulation, submodel, surface fire, wildland fire behaviour
Cluster 11	Physics-Based Fire Spread Modeling, Model Development, and Parameterization	albini, contribution, energy conservation principle, fireline intensity, first part, flame geometry, flame length, formula, growth, independent fire, numerical example, parametrisation, present study, second part, slope, terrain slope, wildfire propagation
Cluster 12	Experimental and Theoretical Ignition Studies	cellulose fuel bed, discrete fire, fall, fire fighter, flammable vegetation, frequency, hot particle, hot spot ignition theory, laboratory, natural fuel, particle size temperature, spherical source, theoretical study
Cluster 13	Numerical Simulation and Computational Research	description, efficiency, error, main feature, numerical simulation, phyfire, research group, salamanca, scientific computation, simulation result, university

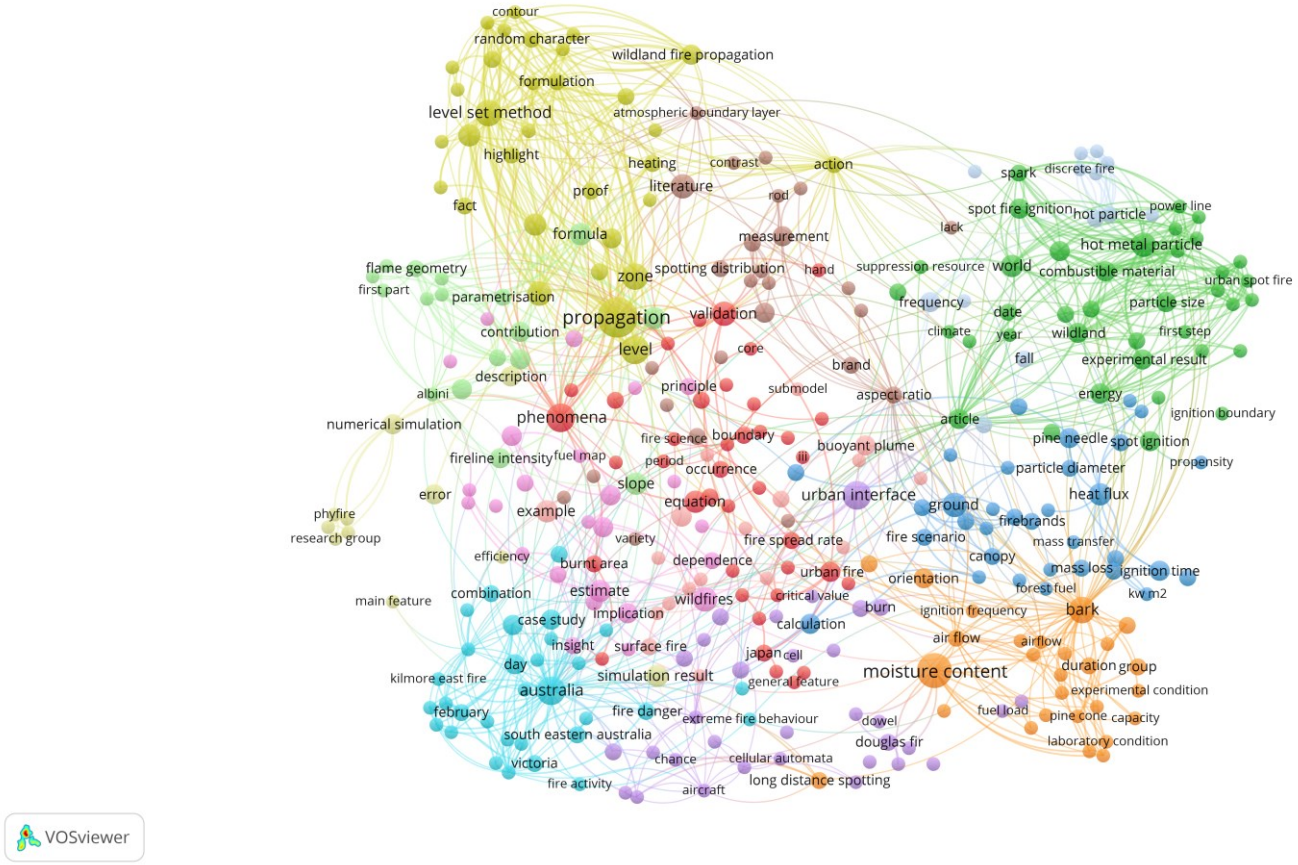


Figure S9. Term co-occurrence network visualization based on the Text Data (based on the full title and the abstract fields).

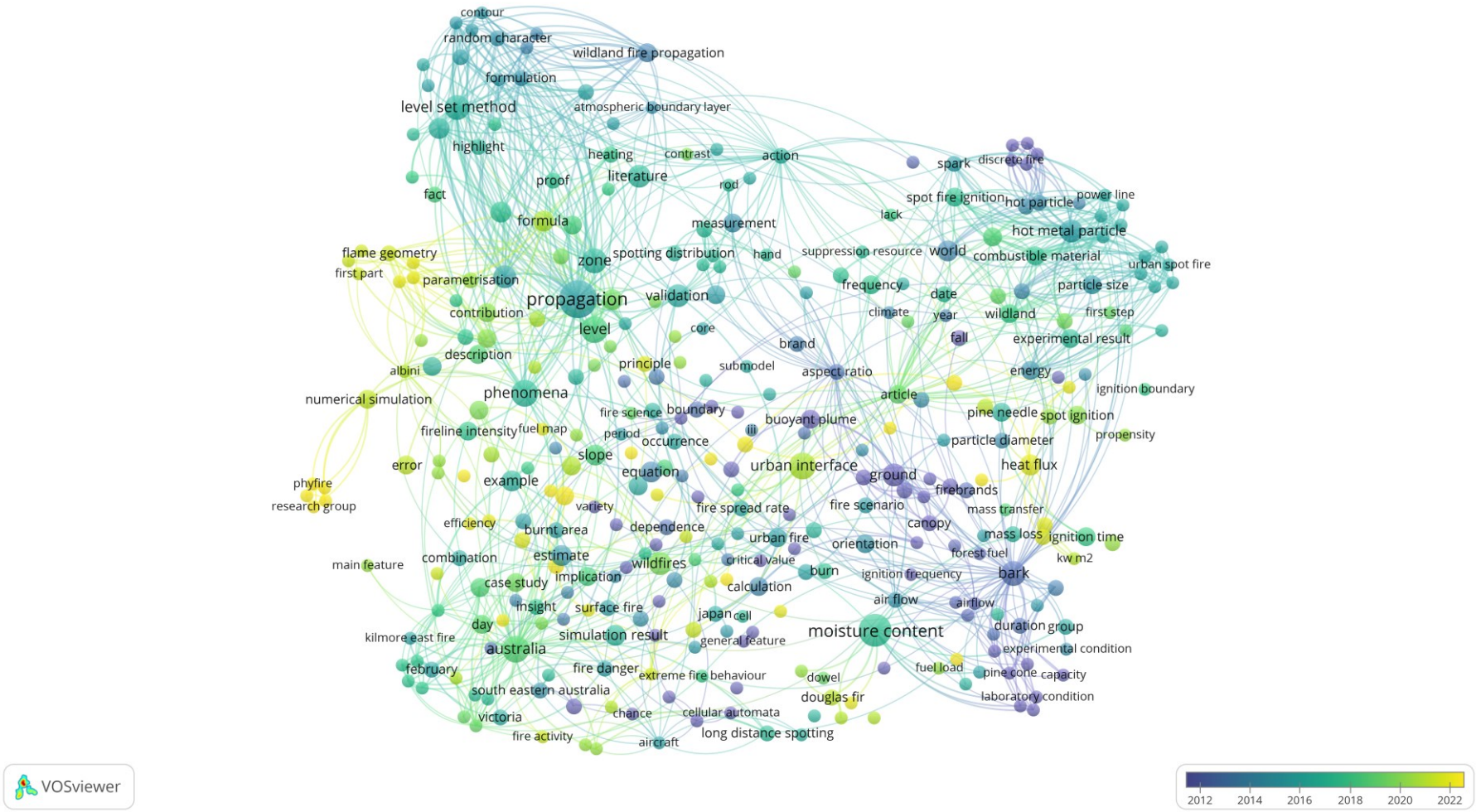


Figure S10. Term co-occurrence overlay visualization based on the Text Data (based on the full title and the abstract fields.



Figure S11. Term co-occurrence density visualization (item density) based on the text data (based on the full title and the abstract fields).

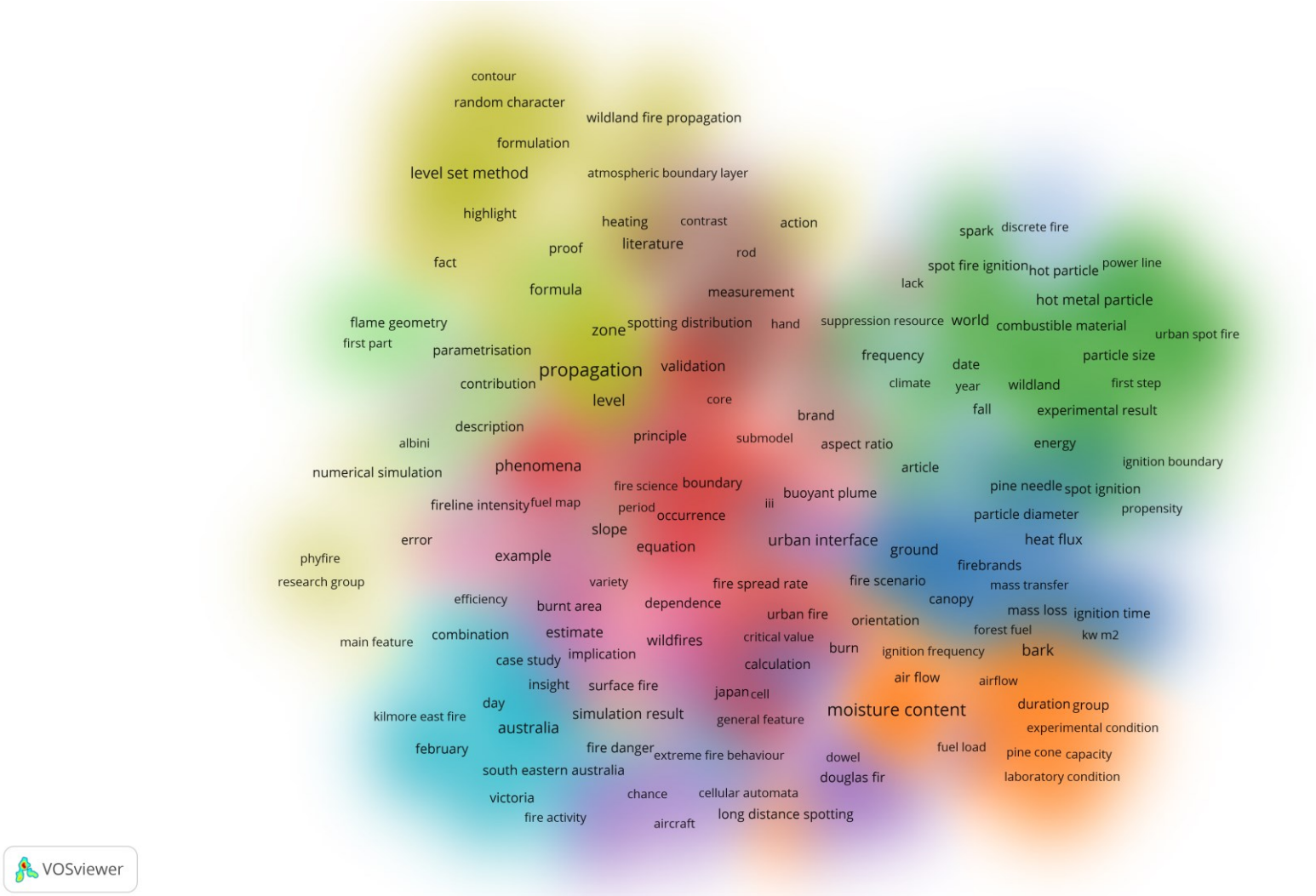


Figure S12. Term co-occurrence density visualization (cluster density) based on the text data (based on the full title and the abstract fields).

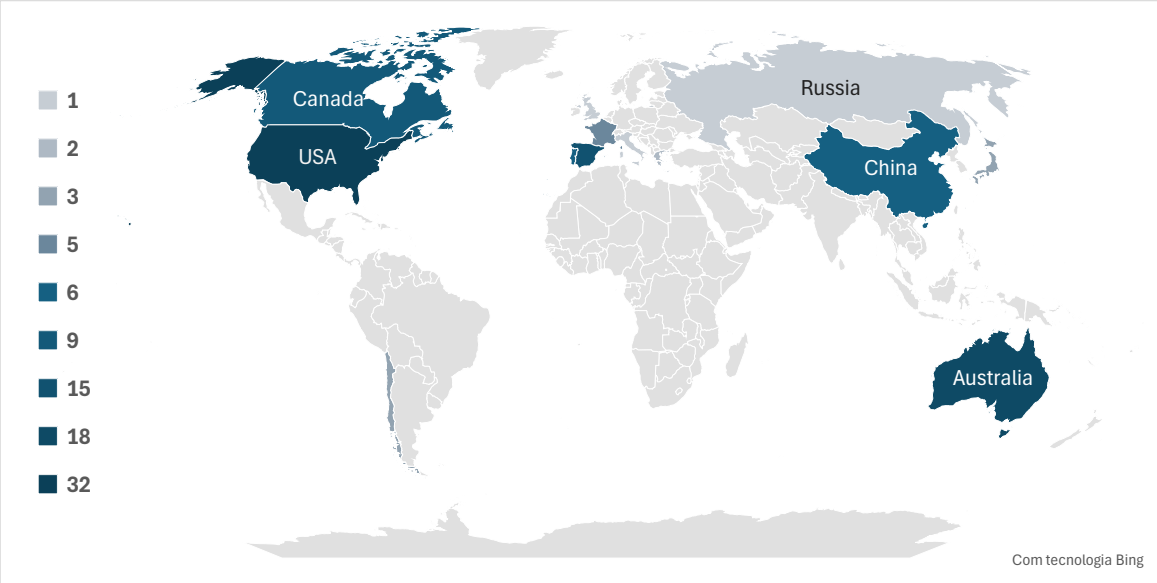


Figure S13. (A) - Geographic distribution of contributions by country (2000-2023).

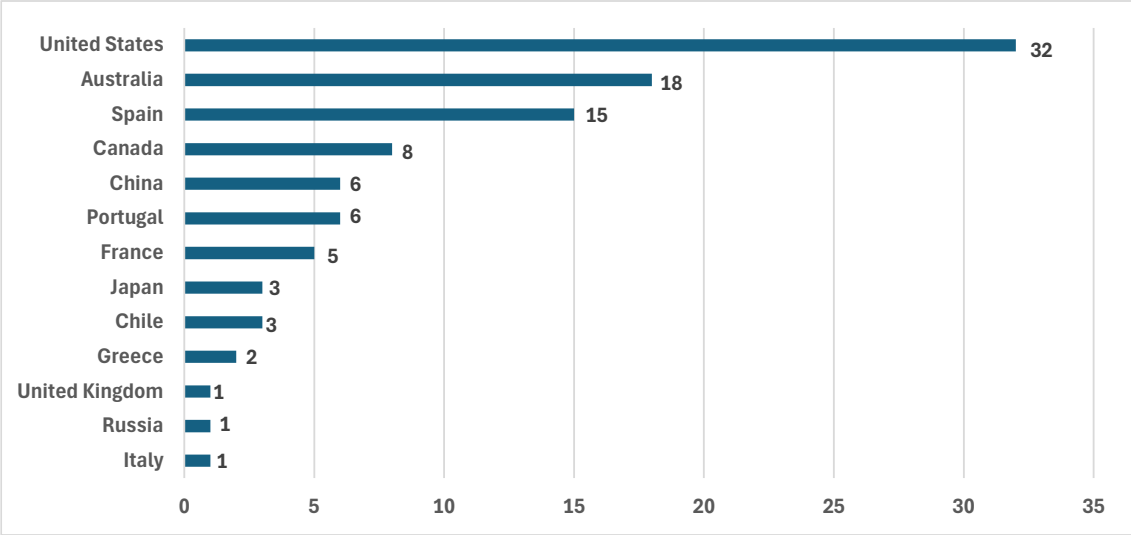


Figure S14. (B) **-** Ranking of contributions by country (2000-2023).

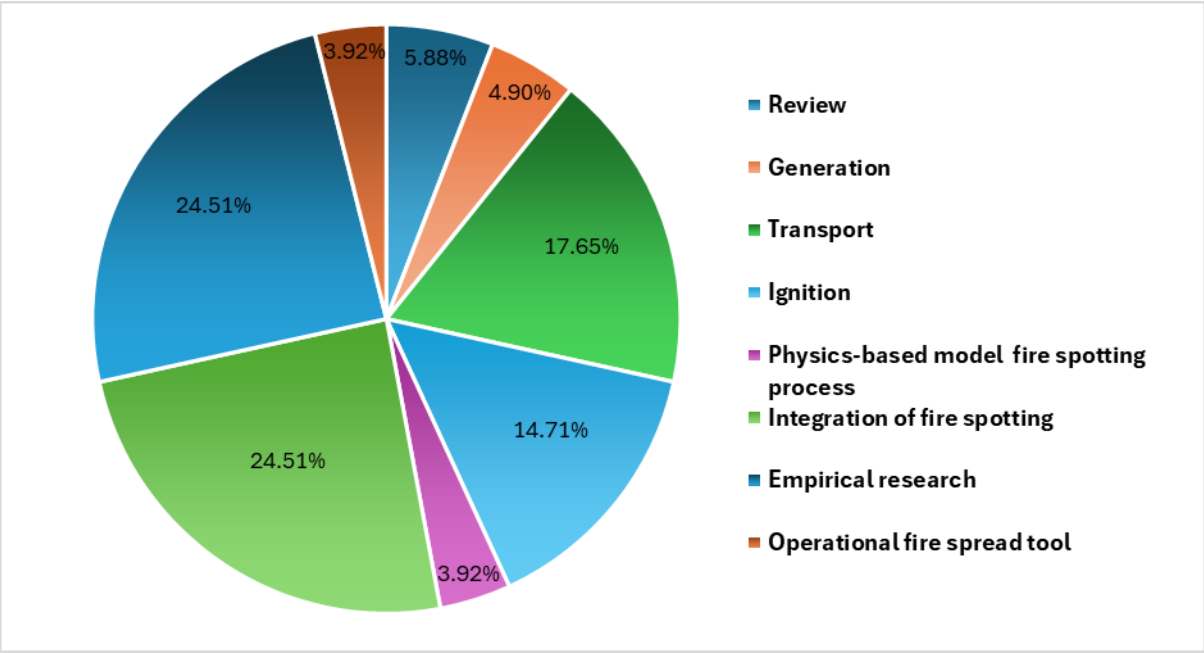


Figure S15. Distribution of research focus areas in fire spotting modeling (102 studies).