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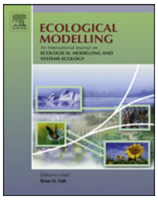

Fuel modelling in terrestrial ecosystems: An overview in the context of the development of an object-orientated database for wild fire analysis

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ABSTRACT

Wildfires are a serious problem affecting many terrestrial ecosystems and causing substantial economic damage. Understanding the variation in structure of fuels (which are predominantly represented by plant litter and live vegetation) is key to understanding the behaviour of wildland fires. An understanding of changes to fuels as vegetation develops is also central to the management of both wildfire and the planning of prescribed burning. A description of fuel structure is required for all models of fire behaviour. It is therefore important that we have an appropriate system for describing fuel structure and predicting how fuel structure will develop through time (*i.e.* fuel succession). In this paper we review the range of published models used for fuel description and fuel succession. We propose an object-orientated database as an appropriate method for storing the complex data structures that are needed to process and analyse data on fuels. The potential advantages of an object-orientated database as a tool for modelling fuel succession are discussed.

1. Introduction

Wildfires are a serious problem affecting many terrestrial ecosystems and causing substantial economic damage (Butry et al., 2001; NIFC, 2003). Wildfires particularly create damage in the wildland–urban interfaces that total hundreds of millions of dollars annually in the United States (Mercer and Prestemon, 2005) and can also affect human life severely: around 100 people were killed by wildfire in Europe in 2007, with Greece and Italy most affected (Lampin-Maillet et al., 2009). Fire is currently a major disturbance on the Canadian boreal forest (Amiro et al., 2001). In Europe, fire is the most important natural threat to forests and wooded areas of the Mediterranean Basin, with an average area burned annually of approximately 600,000 ha (Goldammer and Mutch, 2001). Many large fires are linked with the dramatic land transformation that has been taking place in the Mediterranean region for some decades and which is increasing the risk of forest fire. On the one hand, agricultural fallows and abandoned orchards are slowly being colonised by vegetation whilst, on the other hand, forest is not sufficiently exploited; both result in the increased accumulation of fuel (de la Cueva et al., 2006; Duguy et al., 2007; Lampin-Maillet et al., 2009; Lampin et al., 2007; Pinol et al., 2005). Forest fire hazard is increasing both within forests and also in wildland–urban interfaces where blocks of woodland and shrubland are connected to urban systems (Lampin et al., 2007).

The occurrence and intensity of wildfire are the main elements of fire hazard (Blanchi et al., 2002) which depend (in part) on the availability and characteristics of the fuel (Fernandes et al., 2004; Jappiot et al., 2001). In rural landscapes, fuel is predominantly represented by plant litter and live vegetation. Fuels can be classified as either 'fine fuels' (grass, needles, leaves and thin twigs) or 'coarse fuels' (large branches, snags and logs). Fuel types can also be classified in relation to their organisation into vertical layers (Sandberg et al., 2001) or to their horizontal structure (Riano et al., 2002).

Therefore, a comprehensive collection of the information relevant to the description of plant/litter fuel complexes, fire occurrences, and the relevant environmental variables is needed to enhance the understanding of this phenomenon (and therefore our ability to design effective preventive and mitigating measures). This paper gives an overview of modelling approaches used for the analysis of wildfire fuels and the understanding of their dynamics, and argues the case for an object-orientated database of fuel complexes. In particular, we report on the development

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of such a database within the ‘Fire Paradox’ project funded by the European Union under the Framework 6 Programme (see http://www.fireparadox.org/project_summary.php). In this paper we describe the database structure, and give a brief description of the underlying models, user interfaces, capabilities to incorporate allometric relationships, and the links with relevant process models.

2. Modelling of vegetation and fuel succession in terrestrial ecosystems—an overview

Vegetation flammability and fire behaviour are strongly related to phytomass structural characteristics and depend on the nature and the organisation of the different vegetation layers. Fires burn with highly variable intensities according to fuel structure (Agee, 1998). Forest fire behaviour prediction systems, *e.g.* the semi-empirical model BEHAVE (Andrews and Bevins, 2003; Andrews et al., 2005) based on the model of Rothermel (1972), require the forest fuels to be described in a particular way in which certain wildland fuel characteristics are represented by average values, according to vegetation types. Fuel models are thus the main inputs to the various models for calculating the physical parameters of a fire. Whether one is using complex physical models of the fire, or simpler combinations, it is necessary to identify homogeneous vegetation types, according to the composition and the structure of their combustible biomass. The set of these representative values is called a “fuel model”, but here we will use the term “fuel model” in a broader sense in order to accommodate any quantitative description of fuel.

The first simple fuel models (qualitative descriptors such as herbaceous, bushes, forest) date back more than a century (Dubois, 1914). Then, with the development of mathematical models of fire behaviour such as that of Rothermel (1972), more elaborate fuel models were developed. These models, initially devised for North American vegetation, were then adopted to Spanish forests by ICONA (ICONA, 1993), but restricted to behaviour of surface fires. Anderson provides a key to assigning fuel models by vegetation type (Anderson, 1982).

Hence, knowledge of the vegetation and its successional development and structural dynamics is essential for effective fuel management for controlling fire risk, specifically in the context of climate change. A recent paper (Cary et al., 2006b) reviews the main landscape-fire-succession models and their potential application to predict fire spread and ignition. Below we give an overview of the modelling approaches relevant in this context.

2.1. Allometric models

Allometric relationships between the major dimensions of plants (mostly shrubs and trees) have been known for a long time. They are regularly used for practical purposes, *e.g.* estimation of timber production and quality (Gong and Ong, 1995; Houllier et al., 1995; Nissen et al., 2001), production of the snag deadwood by differently aged forests (Ferguson and Archibald, 2002), assessment of soil respiration and carbon balance (Yang et al., 2007), and estimation of variations in carbon concentrations in various plant compartments, including shoots and roots (Bert and Danjon, 2006). Recently, allometric equations have increasingly been used in conjunction with remote sensing techniques (Balzter et al., 2007; Koetz et al., 2008) and even proved useful in validating remote sensing measurements (Korpela and Tokola, 2006). Literature provides data for shrubby vegetation (matorrals, moorlands, heathlands) and forest vegetation (major forest ecosystems such as pine and oak forests). Most models of fuel accumulation relate the main plant (fuel) characteristics such as phytomass and bulk density to the hypothetical age of fuel (*i.e.* stand age) using the time since the last fire or other disturbance events (but rarely to the real measured age of plants). This generally leads to the construction of fuel accumulation curves (Abdelmoula et al., 2004; Fernandes and Rego, 1998). The temporal description of fuel load is abundantly portrayed in Australian literature (Birk and Simpson, 1980; Burrows and Mccaw, 1990; Fensham, 1992; MarsdenSmedley and Catchpole, 1995; McCaw et al., 2002; O’Connell, 1987) in relation to the widespread practice of prescribed burning. Fuel accumulation modelling usually involves estimation of a steady-state fuel load and of a decomposition constant, after Olson (Olson, 1963). Dynamic fuel models (Agee, 1998; Fernandes and Rigolot, 2007; Hough and Albini, 1978; Rothermel and Philpot, 1973; Schimmel and Granstrom, 1997) offer the possibility of examining how flammability and fire behaviour change with the structural modifications that time induces on the fuel complex.

Most allometric models are empirical equations for calculating the values of an important dependent variable (*e.g.* total stand biomass, biovolume of particles of certain diameter) from the values of other biometrics (*e.g.* average plant height, diameter at breast height) and (sometimes) environmental (*e.g.* soil type, altitude, herbivore pressure) variables that are known or relatively simple to estimate. The major relationships have been established between biomass and plant height, diameter (basal diameter or diameter at breast height), and crown dimensions, including crown width and height (Brown, 1976; Halpern et al., 1996). For instance, Halpern et al. have derived 152 regression equations for predicting aboveground biomass of plant species in an early successional forest (Halpern et al., 1996). Brown (1976) gives linear regression equations for estimating shrub biomass and leaf weight from basal stem diameter.

Allometric growth models used for fuel succession modelling are based on field measurements of different fuel types, often organised along gradients of post-fire succession. There are a number of techniques used to collect the data necessary for deriving the allometric relationships (Catchpole and Wheeler, 1992), including, *e.g.* visual obstruction (Benkobi et al., 2000; Davies et al., 2008), clipping and weighing, and remote sensing (Bongers, 2001; Egan et al., 2000).

Arguably, the best examples of allometric models relate to the studies of various species of gorse. For example, Mediterranean gorse (*Ulex parviflorus*) has been described both as a degradation stage of forest communities after fire, and also as a fire-prone community. Mature Mediterranean gorse shrublands are communities with high biomass (3000–4000 $g\,m^{-2}$) and high horizontal and vertical vegetation (and therefore fuel) continuity, in which the proportion of fine dead fuel fractions with low moisture content is around 50% of the total phytomass present (De Luis et al., 2006). There are detailed accounts of its vegetative structure (plant density, species composition, biomass fractions, and horizontal and vertical fuel distribution) and analyses of fire behaviour using indicators obtained at different scales.

Baeza et al. (2006) showed that in fire-prone species, like Mediterranean gorse that accumulates standing dead fuel, susceptibility to fire is a function of fuel load, vegetation composition and fuel cover, and these characteristics change with time (Baeza et al., 2006), from the youngest stage to the senescent stage. Both phytomass and volume have been shown to increase with time. Furthermore, significant seasonal differences in the characteristics of certain fuel particles may be observed, although that primarily relates to reproductive organs (see a study of *Ulex europaeus* by Puentes and Basanta, 2002).

2.2. Phytosociological succession models

Phytosociological succession models (Lee et al., 1986; McIntosh et al., 2003; Quezel, 1999; Quezel and Barbero, 1989;

VanderMaarel, 1996; Zavala and Zea, 2004) are directly inherited from vegetation ecology (phytosociology, phytoecology, forestry). They provide schemes and pathways from one vegetation type to another along post-fire gradients, or disturbance gradients. For example, these models show how the composition and physiognomy of a matorral evolves during the post-fire regeneration process (Trabaud, 1991); similar studies exist for woodlands (Trabaud et al., 1985a). The models were constructed using a typology first proposed by Trabaud (1977) accounting for vegetation structure, biovolume, specific composition and conditions of fire fighting.

For instance, potential climate-induced vegetation changes in mountain forests of Central Europe and possible impacts on species richness were evaluated in terms of prospective changes in vegetation (Kienast et al., 1998). The spatially explicit forest simulator showed that under a temperature increase without simultaneous increase in precipitation (*i.e.* climate becoming warmer and more xeric due to increased evapotranspiration), the communities in the colline-submontane belt may change from beech-dominated to oak/hornbeam-dominated communities. In the montane belt, the dominance of conifers may be jeopardised by an invasion of deciduous species. Under warmer and wetter conditions the changes may be less pronounced and the shift towards oak and oak–hornbeam communities on the Plateau is unlikely. This analysis is highly relevant, as changes in vegetation type will inevitably result in changes of fuel characteristics and hence fire regimes.

Another noteworthy example relates to the coexistence of Aleppo pine (*Pinus halepensis* Mill.) and Holm oak (*Quercus ilex* L.), two of the most widely distributed species in the Iberian Peninsula, in relation to gradients in water availability and disturbance (Zavala and Zea, 2004). It was found, using a spatial model of landscape forest dynamics, that a shifting mosaic of both taxa can be explained by a competition–colonisation tradeoff (in mesic homogeneous environments) and by a tradeoff between shade and drought tolerance (in heterogeneous low disturbed environments). This analysis furthers our understanding of biological mechanisms underpinning changes in fuel characteristics of the Iberian Peninsula.

It should be noted, that although these models generally do not directly provide us with accurate data for fuel modelling, they help the understanding of fuel succession. However, some studies also include data on fuel biomass (Trabaud, 1991; Trabaud et al., 1985a,b). Importantly, some of these models, and in particular those adapting the vegetation state transition modelling approach, have been embedded in the management-orientated tools, including *e.g.* CBSUM (Keane et al., 1996a), VDDT (Beukema and Kurz, 2000), and RBCLM (McIntosh et al., 2003).

2.3. Gap models

Gap models are specific vegetation models that describe vegetation dynamics (generally vegetation recovery and regeneration) in gaps created by disturbances (Menges and Hawkes, 1998; Miller and Urban, 1999a,b; Scheller and Mladenoff, 2007). These models have been successfully applied to the analysis of various structural vegetation types, including, *e.g.* grasslands (Coffin and Lauenroth, 1994), forests (Desanker and Prentice, 1994), savannas (Acevedo and Raventos, 2002; Raventos et al., 2004), forest–savanna transitions (Favier et al., 2004), and shrublands. In addition to the papers describing specific applications, there are some useful relevant reviews on the subject (Perry and Enright, 2006; Scheller and Mladenoff, 2007; Yemshanov and Perera, 2003), in particular in relation to the Mediterranean area (Pausas, 1999b)—an important location from the perspective of the fire research. When applied on the extended spatial scale, gap models are also relevant to the studies of landscape dynamics and mosaics (Acevedo et al., 1995, 2001; Favier and Dubois, 2004; Wimberly, 2006; Yemshanov and Perera, 2003).

The literature thus includes gap models applied to disturbance by fire, and a number of examples are briefly described below. Fuel dynamics is both the accumulation of live and dead biomass and the development of horizontal and vertical structure as succession proceeds within the gap. Species involved in the succession are likely to be those located in the vicinity of the burnt area, or within the burnt area (especially for plants having fire-resistant seed banks). Bonnet et al. focused on the influence of spatial characteristics of the burnt area on plant regeneration (Bonnet et al., 2002). They examined the effects of distance from unburnt areas on the post-fire dynamics, through the distribution of the seed rain and through variation in soil characteristics.

The spatially explicit and process-based model FORSPACE, featuring a stochastic forest fire simulator, was used to analyse the effects of interactions between the density of ungulates and forest fires on forest dynamics (Kramer et al., 2003). The results suggested that a high frequency of fires may shift the system into an alternative stable state in the phase plane of producers (represented by total ecosystem foliage biomass) vs. consumers (represented by total ecosystem ungulate biomass). Fuel load, however, would be reduced with increased grazing, thus decreasing the frequency of wild fires.

Controls of disturbance (wind and fire) at the transition between prairie, northern hardwoods, and boreal forest in the Great Lakes region of the United States were studied using a generalised vegetation model LPJ-GUESS, combining detailed representations of population dynamics with the mechanistic representations of plant physiological processes. Simulations of vegetation structural and compositional dynamics suggested strong controls on species composition and stand biomass (Hickler et al., 2004).

Tatoni et al. studied the changes on cultivation terraces after land abandonment in the French Mediterranean region using a synchronic approach with two main descriptors: vegetation and soil (Bonnet et al., 2002; Tatoni et al., 1994). They showed that without disturbance, abandoned terraces are quickly recolonised by vegetation that follows succession towards forest. These dynamic patterns are similar to those observed in many other studies of secondary successions. However, wild fires can lead to the development of low open shrublands and changes to the soil, in particular to the granularity of the lower soil horizons.

A spatially explicit forest gap model was developed for the Sierra Nevada, California, to investigate interactions amongst climate, fire and forest pattern (Miller and Urban, 1999b). Fuel inputs in the model are generated from each individual tree according to tree size and species, whilst fuel moisture varies both temporally and spatially with the local site water balance and forest condition, thus linking climate with the fire regime. Fires occurrence is modelled as a function of the simulated fuel moisture and fuel loads, and the burnable area depends upon the spatially heterogeneous fuelbed conditions. It was found that fuel loads limit the spatial extent of fire, whilst fuel moisture exerts an important control on fire frequency (Miller and Urban, 1999a).

Simulations with fire as an agent of partial disturbance using the FORCLIM model of forest dynamics suggested that frequent fires of low severity can alter forest composition and structure as much or more than severe fires at historic frequencies (Busing et al., 2007). The model was successfully tested using field survey data, and also for its ability to capture successional trends in ecoregions of the west Cascade Range (USA). It was then applied to simulate present and future (1990–2050) forest landscape dynamics.

A model GREFOS, specifically adapted to the Mediterranean setting, was used to explore scenarios of changes in the fire frequency (Fyllas et al., 2007). It was shown that pioneer pine species appear to be able to enhance their abundance, at both the upper altitudinal limit of typical Mediterranean forest communities and the lower limit in temperate forests.

A mechanistic ecological process model for simulating fire succession was used to evaluate cumulative effects of various fire regimes, including prescribed burning and fire exclusion, on the vegetation and fuel complexes in coniferous landscapes (Keane et al., 1996b).

Simulations using FORSAT, a stochastic cellular automaton model, showed that two parameters (an environmental factor and anthropogenic fire frequency) control the phase transition between forest and savanna in Africa (Favier and Dubois, 2004).

Two simulation models of vegetation dynamics (*i.e.* FATE – based on vital attributes – see below, and BROLLA—based on the gap-phase theory) were used to predict changes in plant functional types due to changes in fire recurrence in eastern Spain (Pausas, 1999a). Four functional plant types, based mainly on their regenerative strategies after disturbance, were considered: *Quercus* (resprouter), *Pinus* (non-resprouter with serotinous cones), *Erica* (resprouter), and *Cistus* (non-resprouter with germination stimulated by fire). At intermediate recurrence scenarios, the simulations by both models suggested a decrease in *Quercus* abundance, an increase in *Cistus* and *Erica*, and a maximum of *Pinus*, thus implying corresponding changes in fuel loading and structure. This study leads us to a more detailed consideration of the vital attribute models.

2.4. Vital attribute models

The notion of vital attributes (Bradstock and Kenny, 2003; Cornelissen et al., 2003) relates to functional classification of traits determining the survival, regeneration and dispersal dynamics (Noble and Gitay, 1996; Noble and Slatyer, 1980). For example, in a study of leaf traits and resprouting ability in the Mediterranean Basin, a number of leaf-related indicators were measured for over 30 woody species (Paula and Pausas, 2006). The authors found a physiological tradeoff between drought resistance and carbon gain. Non-resprouters were shown to have higher potential for structural resistance to drought and higher water-use efficiency than resprouters.

The dynamics of specific plants or groups of plants (functional groups) relates to their fire resistance and fire regeneration strategy (Ojeda et al., 1996). The major plant traits used are vegetative traits, leaf and root traits, and regenerative traits (dispersal mode, resprouting capacity, etc.) (see Cornelissen et al., 2003). This has produced a large amount of literature on plant functional traits and groups, with a special emphasis on the major contrast between seeders and resprouters.

Gachet et al. developed an ecological Mediterranean flora database, BASECO, with the botanical and ecological characteristics of about 1800 plants (Gachet et al., 2005). Each species is characterised by several qualitative traits relating to morphology, reproduction, life forms and biogeographical distribution.

The models addressing vital attributes belong to a wider range of models that describe post-fire vegetation recovery, those using the major plant traits that condition their survival, regeneration and dispersal dynamics (Ojeda et al., 2005). This approach may be used in conjunction with the Gap Models (Pausas, 1999b) discussed above. In some cases the vital attributes concept is formally incorporated into the structure of gap models (Pausas, 1999a).

Certain plant functional traits may have resulted as an evolutionary adaptation in fire-prone communities; *e.g. P. halepensis* is known to have very little regeneration under mature plants, but is characterised by high production of serotinous cones, in particular in younger plants (Lloret et al., 2003). This strategy increases the seed bank, whilst the high resin content increases the probability of canopy fires and consequent death of the parent trees. The high pH of the ash-bed under the burned canopies favours the post-fire regeneration niche of *P. halepensis* under their parent trees; the seedlings grow quickly and reproduce at an early age. These traits are advantageous for post-fire regeneration, and might have been selected during the time scale of anthropogenic fires in the Mediterranean Basin (Bautista and Vallejo, 2002; Lloret et al., 2003; Trabaud et al., 2002).

The Plant Functional Type approach relies on the assumption that some groups of plants react in a similar way after fire disturbance (Paula and Ojeda, 2006; Paula and Pausas, 2006). It has been argued that Plant Functional Type should be considered within a hierarchical IPCD framework: individual-persistence capacity, propagule-persistence capacity (*i.e.* at the population level), competitive capacity (persistence at the community level) and dispersal capacity (persistence at the landscape level) (Pausas and Lavorel, 2003).

In another example, coexistence of *P. halepensis*, *Quercus coccifera*, *Erica multiflora*, *Rosmarinus officinalis*, *Cistus albidus*, *C. salviifolius* and *Ampelodesmos mauritanica* (all Mediterranean species with contrasting life history traits), has been studied under different fire scenarios using data from a field survey and simulations with the FATE vegetation model (Lloret et al., 2003). Higher fire frequencies corresponded to an increase in the resprouting and dominance of *Ampelodesmos* grass, and small increase of *Erica*, and a decrease in *Quercus* and *Pinus* abundance (the latter may even disappear). *Rosmarinus* and *Cistus* (the seeders) were characterised by an increase in abundance at intermediate fire frequencies.

Kazanis and Arianoutsou (2004) developed a hierarchical approach for plant functional classification to describe long-term vegetation change in burnt *P. halepensis* forests. Twenty-nine different functional groups were created (14 for woody and 15 for herbaceous species). A negative relationship was found between the abundance of woody obligate resprouters and the regeneration of woody obligate seeders (Kazanis and Arianoutsou, 2004).

2.5. Plant architecture models

Plant architecture models (Acevedo and Raventos, 2002; Castel et al., 2001; Corradini and Clement, 1999; De Luis et al., 2004; Fulbright, 1996; Godin, 2000; Keane et al., 1996c; Kurth, 1994; Matlack, 1997; Perrin et al., 2001) are mostly stemming from agronomy and forestry, and there are also other applications, *e.g.* in paleobotany (Daviero and Lecoustre, 2000) and urban planning (Perrin et al., 2001). The major objective of these models is predicting plant growth and form (and sometimes plant growth anomalies) throughout the plant's life, and in reaction to different stresses such as fire, competition, and management practices (*e.g.* tree thinning). Usually, plant architecture is studied as a probabilistic or physiological process.

In the context of wild fire, noteworthy examples relate to the modelling of savanna grasses (Acevedo and Raventos, 2002; De Luis et al., 2004) and the inhibition of community succession in heathlands, where growth of dense colonies of *Polytrichum commune* following a fire prevents reestablishment of the typical heathland formation (Corradini and Clement, 1999).

The recent advances in plant architecture rely on 3D digitising of plants through their life cycle or after a specific treatment, often using the data of remote sensing (Castel et al., 2001). These measurements are modelled in relation to ecophysiological parameters. Specific models exist for *P. halepensis* and *Q. ilex*. Simple but effective field studies exist (Puentes and Basanta, 2002).

The plant architectural software AMAPsim (Caraglio et al., 2007) relying on both qualitative and quantitative tree architecture description and leading to realistic 3D computing trees, has been used to complement fuel characterisation. Spatialised data including physical parameters has been extracted and then used in physical-based fire propagation models like FIRESTAR and FIRETEC.

2.6. Landscape dynamics and mosaics models

These models (Busing et al., 2007; Keane et al., 1996c; Pausas, 2006; Wimberly, 2006; Yemshanov and Perera, 2003) may interlink/incorporate the approaches already discussed (see Cary et al., 2006a for a review); for example the approach of vital attributes is useful for the analysis of landscape dynamics (Pausas, 2006). The models of this type could address the issues of *e.g.* species competition, landscape engineering, landuse planning. Importantly, some of the available software is management-orientated; for example, TELSA (Kurz et al., 2000) uses the VDDT tool mentioned earlier. Given the constraints on space, only a couple of noteworthy examples will be described below in some detail.

Mouillot et al. developed the simulation approach called SIERRA for a *Q. ilex* stand, and for the fire-prone community dynamics of a maquis shrubland in Corsica. The influence of fire on vegetation dynamics was modelled from vital attributes, whilst spatial processes of seed dispersal and fire spread were used to simulate landscape heterogeneity (Mouillot et al., 2001).

A mechanistic, biogeochemical succession model, FIRE-BGC, was used (Keane et al., 1996b) to investigate the role of fire on long-term landscape dynamics in northern Rocky Mountain coniferous forests of Glacier National Park, Montana, USA. FIRE-BGC is an individual-tree model-created by merging the gap-phase process-based model FIRESUM with the mechanistic ecosystem biogeochemical model FOREST-BGC—that has mixed spatial and temporal resolution in its simulation architecture. Ecological processes that act at a landscape level, such as seed dispersal, are simulated annually from stand and topographic information. The model also explicitly simulates fire behaviour and effects on landscape characteristics.

2.7. Climate models

There are two principal links between the models directly or implicitly incorporating fuel modelling and climate models. Firstly, the outputs of the climate models (*e.g.* future changes in temperature and precipitations) are often used to simulate 'What if' scenarios using the various other types of models described above. Thus, predictions of ecosystem responses (including *e.g.* changes in forest composition and structure) to climate warming are often made using gap models (Desanker, 1996; He et al., 2005). For instance, a gap model LINKAGES was coupled with a spatially explicit landscape model LANDIS, that incorporates spatial configurations of the simulated forest ecosystems, seed dispersal and fire disturbance, to study the responses (establishment) of individual species to climate warming (He et al., 2005). The study used predictions of the Canadian Global Coupled Model (CGCM2) for the Changbai Mountain area to address potential changes in temperature and precipitation.

Secondly, certain outputs of the fuel models, and of the fire behaviour models, are used as inputs in the models of climate change in relation to *e.g.* the budget of greenhouse gasses, changes in albedo, alterations of water balance, and changes in biodiversity. Hence, modelling of fuel in terrestrial ecosystems is also relevant to the development of theories and methods underpinning investigations of indirect effects in ecology and environmental sciences (Krivtsov, 2004a,b).

3. The FireParadox fuel database

The brief review of fuel succession models above shows the wide range of different approaches that have been taken by different authors. These operate at a wide range of both temporal and spatial scales and different classes of models may use completely different ways of describing fuels. Equally, different groups of researchers will use very different methods for describing and measuring the characteristics of fuels that they consider important for fuel description and classification. Any database system that has to collate the information on fuels necessary to understand fuel-succession processes must be highly flexible in the type of data that can be stored.

The ecoinformatics community is currently stressing the need of a semantic approach to environmental knowledge, both in data and model harmonisation and integration (Athanasiadis, 2008; Rizzoli et al., 2007, 2008; Wien et al., 2007). Enhanced query engines with inference capabilities and common modelling frameworks are under development. However, a ready-to-use solution is not yet easily available and the development of a project requires the mastering of different instruments like ontology tools and code generation engines.

To create a flexible fuel knowledge database we used an object-orientated structure, mirroring fuel concepts to classes. An object-orientated database can represent the perceived physical structure of fuels in a sufficiently realistic way. Moreover, the methods for each class can specify access and transformation rules, or enhancing query capabilities.

We compared the merits of a relational database (PostgreSQL, MySQL) and an object-relational mapper ORM (Hybernate) with those of an object-orientated database (OODB), like db4o. Given the research character of our repository, and the need to make frequent structural changes as ideas develop, we opted for the OODB. This allows the storage of any complex object structure and permits an easier refactoring and migration of the stored data (this can be quite a tedious job when using an ORM) through the different development steps. The open-source object-orientated database db4o (Paterson et al., 2006) seemed most appropriate with almost "zero" administration; it is widely and increasingly used. Importantly, db4o can be used both with Java and .NET languages, so that future developments will not be constrained. db4o has already been used in different disciplines of natural sciences, and has been successfully tested by Leone and Chen (2007) in the context of an information system for water catchment management.

The fuel repository was developed purely on the Java platform, without the need of additional technologies like XML, ontologies or relational databases (SQL).

3.1. Object structure

In object-orientated data models (OODM), objects are classified according to their properties and behaviour (Bertino and Ooi, 1999). Fuel data are extremely heterogeneous, ranging from small to large spatial scales, and fuel complexes are described according to different organisational approaches (Fig. 1).

Fuel particles can be considered to have a logical structure in the context of fire, and this structure can be mirrored in the structure of the OODB. There are certain common properties of all fuels such as ash content and heat of combustion. However, there may be several different ways of representing fuels at a higher level. Thus, there is a 'biological representation' (Fig. 1) in which particles of fuel, *e.g.* twigs or leaves, each has its own properties of, for example, length and thickness, but also inherits the properties of ash content and heat of combustion. A plant may be considered as a collection of branches. Plants can similarly be aggregated into stands of vegetation.

Alternatively, fuels may be considered as functional strata within the vegetation. Thus duff, litter, grasses, shrubs and tree crowns will have the properties of, for example, thickness and vertical position of the stratum, but do not need to be represented explicitly in the horizontal dimension. These different functional fuel types have unique sets of properties and will be treated differ-

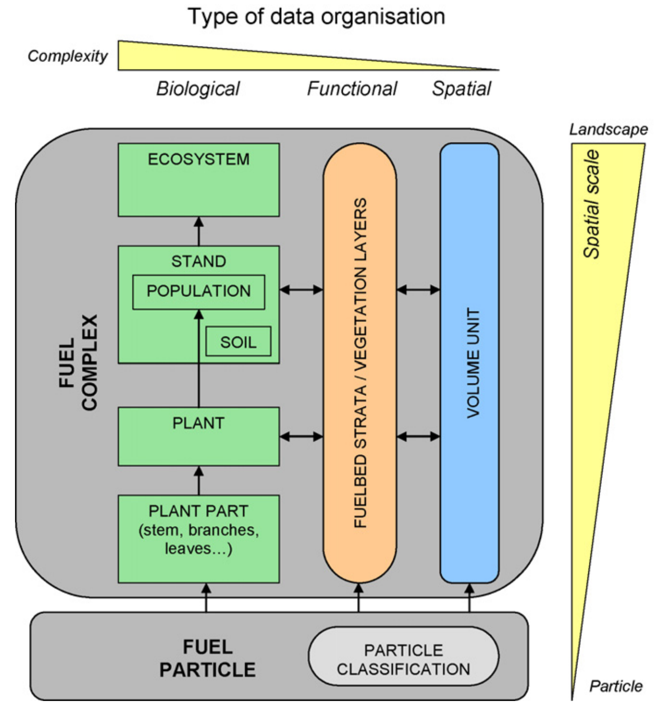


Fig. 1. Conceptual structure of fuel data with examples of some of the different ways in which fuel complexes can be represented. The 'Biological' approach uses a hierarchical classification of fuels reflecting the level of organisation (particle, plant, community); the 'Functional' approach classifies fuels more by their biological functional group (trees, shrubs, litter); whilst the spatial approach describes fuels in a three-dimensional spatial grid.

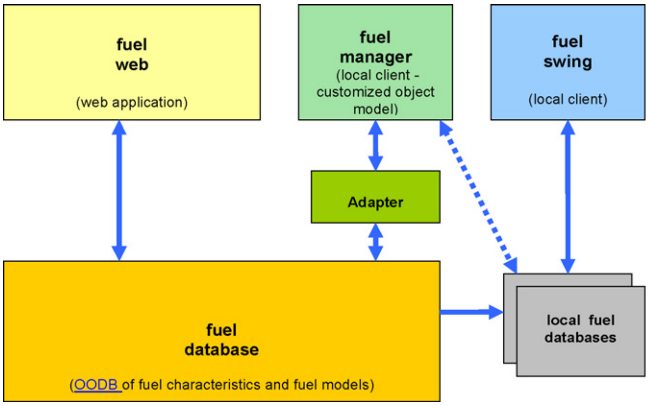


Fig. 2. Architecture of the fuel database and related products. *WebFuel*: Web-based application interface to the fuel database. *FuelSwing*: stand-alone application interface (the user works on a database downloaded from the Web and can access it directly as it is stored on the user's computer). *FuelManager*: customised client application interface developed by INRA. OODB = Object-Orientated Database.

ently in fire models.

Finally, we consider the purely spatial distribution of fuels. In this representation the vegetation is divided into a three-dimensional grid and each cell within the grid contains a collection of fuel particles of different types (*e.g.* twigs and leaves). Individual plants could be considered as three-dimensional collections of cells to form characteristic shapes.

Our data semantic has been implemented into a hierarchic object model. We consider the fundamental unit of the database to be the 'Fuel Particle' with properties of size, moisture content, heat of combustion, etc. Fuel particles are combined in different ways at increasing spatial scales to create fuel complexes, *e.g.* plants, shapes, and layers. This approach has the strong hierarchical complexity above, but retains the compatibility between different representations.

We used two different design patterns to implement the properties of each fuel object. Fundamental properties, necessary for the object definition (*e.g.* taxon of a plant class), have been implemented as class attributes. Optional properties (*e.g.* height of a plant class) have been implemented as objects of the Property class, with a definition (*e.g.* 'biomass'), content, range and domain (object types which are allowed to have this property), and can be added to the Property collection of each fuel object. Further metadata properties can be added to each Property object, *e.g.* the name of the observer, a site name, a reference, or a collection of events. In this sense the developed Property objects are quite similar to the ontological representation of properties.

Whilst this approach has some disadvantages concerning database size and query performance, it gives us flexibility, allowing the creation of fuel objects with different properties, according to the needs of the users, and allowing us to add new properties in the future, without having to change the class structure and refactor the database.

Further information on the data model structure is available elsewhere (Pezzatti et al., 2007a,b).

4. Tools

4.1. Interfaces

The prototype system has a central database, accessible through a rich web interface (FuelWeb) or through specific adapters for custom applications, like the FuelManager (see Section 5). It is possible to download portions of the central database, in order to enable individual users to develop their own fuel succession models locally. To this purpose a local client application (FuelSwing) is also under development. Fig. 2 gives an overview of the architecture of the developed system.

To date, the pilot database has been created for selected data types and successfully tested using both the Web-based (using the Echo2 library) and the stand-alone (using the Java Swing library) interfaces. The FuelManager and its adapter have also been successfully tested. FuelWeb and FuelSwing applications share a set of common libraries, namely the database object model, the data access interface model, the analysis package and the analysis interface model.

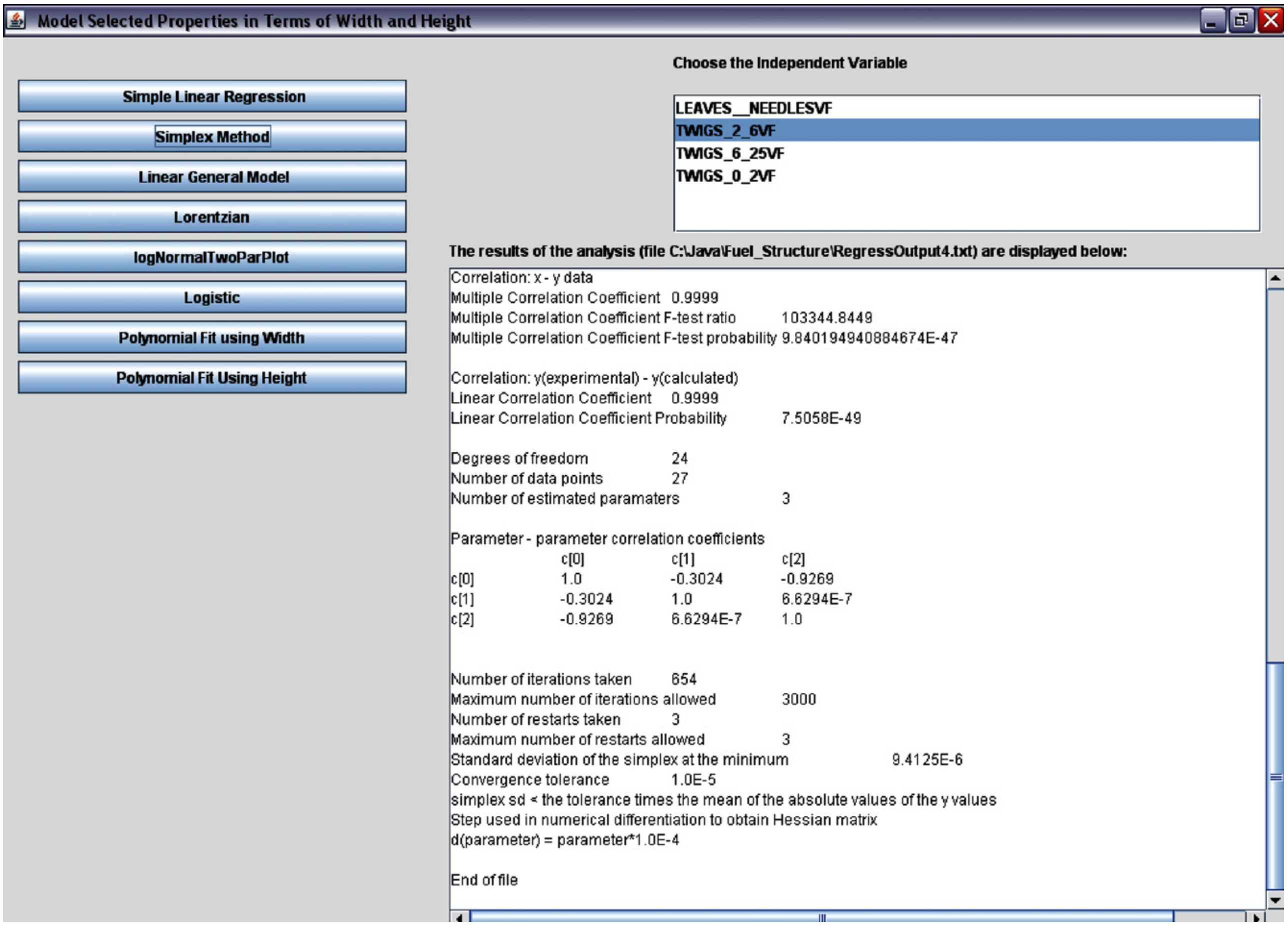
4.2. Analysis tool for allometric relationships

An important part of the application design is the ability to transform and analyse the stored data and to present the information at different levels of aggregation. The suite of mathematical techniques from the scientific library of M.T. Flanagan (UCL) is used as a basis for regression analyses (see Fig. 3). Selected variables can be transformed with built-in or user-defined functions, using on-the-fly compilation. The application allows the user to carry out regression on selected fuel properties for any specific query (*e.g.* volume fraction of small twigs against height and width of plants).

Work is currently underway to test the performance of the allometric analysis using the INRA data, by comparing the outputs with the results previously obtained through the analysis of the primary data stored in a relational database.

5. Fuel Manager: an example of links between the FireParadox OODB and simulation models

In the last two decades, architectural analyses have been used to model plant development and stand structure, thus furthering



Choose the Independent Variable

LEAVES__NEEDLESVF
TWIGS_2_6VF
TWIGS_6_25VF
TWIGS_0_2VF

The results of the analysis (file C:\Java\Fuel_Structure\RegressOutput4.txt) are displayed below:

```
Correlation: x - y data
Multiple Correlation Coefficient  0.9999
Multiple Correlation Coefficient F-test ratio        103344.8449
Multiple Correlation Coefficient F-test probability 9.840194940884674E-47

Correlation: y(experimental) - y(calculated)
Linear Correlation Coefficient    0.9999
Linear Correlation Coefficient Probability           7.5058E-49

Degrees of freedom                24
Number of data points             27
Number of estimated paramaters                       3

Parameter - parameter correlation coefficients
                  c[0]            c[1]            c[2]
c[0]              1.0             -0.3024         -0.9269
c[1]              -0.3024         1.0             6.6294E-7
c[2]              -0.9269         6.6294E-7       1.0


Number of iterations taken        654
Maximum number of iterations allowed                 3000
Number of restarts taken          3
Maximum number of restarts allowed                   3
Standard deviation of the simplex at the minimum                     9.4125E-6
Convergence tolerance             1.0E-5
simplex sd < the tolerance times the mean of the absolute values of the y values
Step used in numerical differentiation to obtain Hessian matrix
d(parameter) = parameter*1.0E-4

End of file
```

Fig. 3. An example view of the 'Allometric' interface.

our understanding of the processes relevant to ecosystem dynamics and susceptibility to fire (Sinoquet et al., 1997). The *Fire Paradox Fuel Manager* is a computer software integrated in the data processing chain between the European data and knowledge base on fuels (which includes the FireParadox OODB) and the 3D physical-based fire propagation models. It is a key application in the fire modelling process with three main functionalities: (i) creation of vegetation scenes in 3D to be used as input data for fire behaviour models, (ii) fire effects visualisation on shrubs and trees, and (iii) fuel succession visualisation after fire occurrence by coupling a vegetation visualisation system with plant growth models.

Fuel Manager has been developed as a module in CAPSIS, a free platform dedicated to host a wide range of forest dynamics and stand growth models (de Coligny, in press; de Coligny et al., 2004). CAPSIS is designed around a kernel which provides an organisational data structure (session, project, scenario steps) and also generic data descriptions (stand, tree, etc.). These descriptions can be completed in modules, one for each model, which implement a data structure and a fuel succession function (growth, mortality, regeneration, etc.) with a chosen simulation time step. A new *Capsis* module – "*FireParadox*" – has been developed which implements data structure and functionalities of the *Fuel Manager*. *Capsis* and *Fuel Manager* are both written in JAVA language.

The application is permanently connected through the Internet to the *FireParadox OODB* and manages three levels of users' rights. *FireParadox OODB* is currently hosted by European Forest Institute servers in Finland becoming a facility of the *FireIntuition* platform. The *Fuel Manager* set of files necessary to install the application as a local client can also be downloaded from the *FireIntuition* platform.

There are several ways to create a vegetation scene including loading of a pre-existing inventory file, creating a vegetation scene from scratch or the automatic generation of a new scene respecting a set of constraints on the spatial distribution of several populations of plants (*e.g.* list of dominant species with specific distributions of height and cover). A special option generates a vegetation scene by loading an inventory file which contains only vegetation objects available from the *FireParadox OODB*. The inventory file describes each vegetation object through its "ID" in the *FireParadox OODB*, and location. This option requires a connection with the remote OODB since species, height and crown dimensions are read for each vegetation object in the database before generating the scene. The inventory file also contains a line describing the dimensions of the terrain. Using this option to generate a vegetation scene makes it possible to create export files necessary to run fire propagation models.

The *Fuel Manager* can be used as a management tool for manipulating fuel complexes. So far, the work carried out in collaboration with the CAPSIS developers has related to the Graphical User Interfaces (GUI), *e.g.* development of 3D visualisation viewers and tools to interact dynamically with the vegetation objects. An editor of 3D vegetation scenes has been implemented allowing interactive manipulation of the vegetation scenes (*e.g.* zoom, rotation, pan) and manipulation of vegetation objects (selecting, adding, updating, moving) through a Graphical User Interface. A vegetation object, *e.g.* a plant, can be added to the scene following several planting patterns (regular, random, clustered) across the whole scene or within a selected polygon. Several renderers are available to display 3D vegetation objects (represented as boxes, lollypops, outlines or complex patterns). Moreover, several tools are available to display descriptive statistics for the vegetation scene content or for the current selection. Forest management tools are available for tree thinning using the tools already implemented under the Capsis platform.

Data related to fuel description are stored in the *FireParadox OODB* with a structure that has been designed on the basis of an inventory of both available fuel data (INRA's cube method—see Appendix A) and expected 3D fuel data from other project partners. A set of dialog windows has been implemented to manage the interactions between the database and the *Fire Paradox Fuel Manager*. The Fuel Editor is a functionality of the *Fuel Manager* implemented mostly to manipulate three fuel categories: fuel samples, fuel plants, and fuel layers (see Appendix A for definitions). Finally, the spatial distribution of vegetation in the whole vegetation scene can be represented by a 3D matrix of volume fractions for each fuel particle considered.

One of the main objectives of the Fuel Manager is to automatically build input files for both 2D and 3D fire behaviour models. The application includes a dedicated export feature which so far creates input files for FIRETEC fire behaviour model based on the selected scene. FIRETEC is a coupled atmospheric transport/wildfire behaviour model being developed at Los Alamos National Laboratory (Linn et al., 2002), and further developed with the collaboration of INRA, Avignon research group (Pimont et al., in press). FIRETEC is a transport function that uses a compressible-gas formulation to couple its physics-based wildfire model with the motions of the local atmosphere. It is based on the principles of the conservation of mass, momentum, and energy. The FIRETEC fire propagation model needs four input binary files containing information related to fuel bulk densities, fuel thickness, wet mass vs. dry mass ratio and fuel height above ground. These input files describe the composition and the structure of the fuel complex taking into account stored data that describe the physical properties of various components of the different layers (trees, shrubs, herbs and litter) composing the vegetation scene. The Fuel Manager exports the various values of the fuel particles properties from the 25 cm side grid of the Fuel Manager into the FIRETEC grid. Under FIRETEC the finest scale to describe vegetation structure that can be reasonably used for calculation is within two meters of the ground.

Ongoing research effort is focused on linking fire model outputs with fire impacts on individual plants with the objective of predicting fire-induced tree mortality. In that perspective, several fire impacts on the crowns and trunks of trees have been defined and can be visualised with the Fuel Manager at the scene scale.

6. Concluding remarks

6.1. Discussion

Correct representation of fuel is indispensable for our ability to predict the likelihood and characteristics of wildfire. Importantly, an understanding of fuel structure is indispensable for the predictions of likely fire damage; for example the probability of mortality in *P. halepensis* and *P. pinea* trees (modelled with logistic regression analysis using data on tree size and fire-damage descriptors from 998 trees in 13 stands) was shown to increase with increasing percentage of crown scorched and estimated depth of bark charring, and with decreasing tree DBH (Rigolot, 2004).

To date, some of the studies have suggested that models of physical fuel properties predicting fire characteristics by broad vegetation types are adequate for practical use (Brown and Bevins, 1986). For example, using 2–3 dominant fuel groups was shown to be adequate for modelling fire behaviour in Rothermel's (1972) fire spread model (Brown, 1981). However, specific data on the biomass of small particles used in fire behaviour modelling are incomplete. The ongoing development of sophisticated fire behaviour and effects models requires a comprehensive system of fuel classification that more accurately captures the structural complexity and geographic diversity of fuelbeds (Sandberg et al., 2001). In particular, there is a need to know quantitative fuel characteristics (physical, chemical, and structural properties) and probable fire parameters specific to the fuelbed in question. Hence, arguably, the most important practical application of our system is likely to stem from its comprehensive capability for allometric considerations. Models relating phytomass to phytovolume are very useful in this respect. Also useful are considerations of chemistry and, especially, moisture content; potentially, knowing structure and weather conditions, one could develop complex dynamic fuel moisture models.

It should also be noted that our approach is considerably more general and flexible than the ones commonly adopted in wildfire ecology. For example, the Canadian system uses fire behaviour models whose parameters vary with vegetation type, *i.e.* the quantitative characteristics of fuels are not an input to the system, which has an obvious limitation. In other systems, *e.g.* BEHAVE/BehavePlus (Andrews and Bevins, 2003; Andrews et al., 2005), a fuel model is a set of fuelbed inputs needed by a particular fire behaviour or fire effects model, *i.e.* a single set of data that describe a particular type of vegetation that can be used to run a fire behaviour model to predict fire behaviour in that particular vegetation. Typically, the input set for a fire behaviour fuel model includes (a) fuel load by category (live and dead) and particle size class (0–0.25 in., 0.25–1.0 in., and 1.0–3.0 in. diameter), (b) surface-area-to-volume ratio by component and size class, (c) heat content by category, (d) fuelbed depth, and (e) dead fuel moisture of extinction.

Usually, there are a number of preset fuel models (*e.g.* 53 in BehavePlus), and the user is supposed to choose from them. However, owing to its generic nature and flexibility, our approach provisions an easy generation of an indefinite number of fuel models exactly reflecting both quantitative and qualitative characteristics of the vegetation present. Generation of input files defining the fuel model has already been implemented in the Fuel Manager for FIRETEC, and development of the interfaces with other fire models is also intended (Legg et al., 2008).

The overview presented in this paper indicates that fuel modelling has a number of important links and overlaps with a whole range of fire and vegetation models. Consequently, the Object Orientated Database developed within the FireParadox project will have a range of useful interconnections depicted in Fig. 4. In particular, in addition to the most important link with fuel models and thus with fire models described above in detail, the FireParadox OODB is likely to be of value wherever detailed quantitative and qualitative information on vegetation is required, *e.g.* in climate change research. The ability of the OODB to store allometric equations as separate objects will be invaluable for research on ecological succession and ecosystem modelling. The FireParadox OODB should also prove useful to a broad range of ecological investigations addressing, *e.g.* interactions amongst forest litter composition, moisture content, surface plant cover, soil properties, and biota (Krivtsov et al., 2004, 2006, 2007), as well as to practical applications of environmental monitoring and management (Curt et al., 2003; Jappiot, 1995; Legg, 2004; Legg and Nagy, 2006).

6.2. Future developments

The currently implemented cube model of a fuel complex is the least hierarchical with landscapes comprising large collections of more-or-less independent fuel descriptions at the cube level. Other

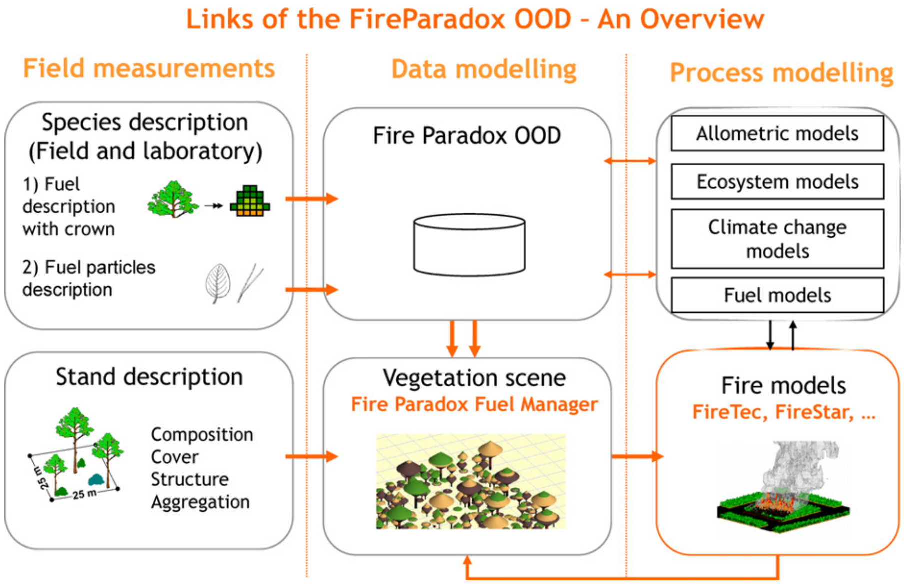


Fig. 4. Existing and potential links of the FireParadox OODB.

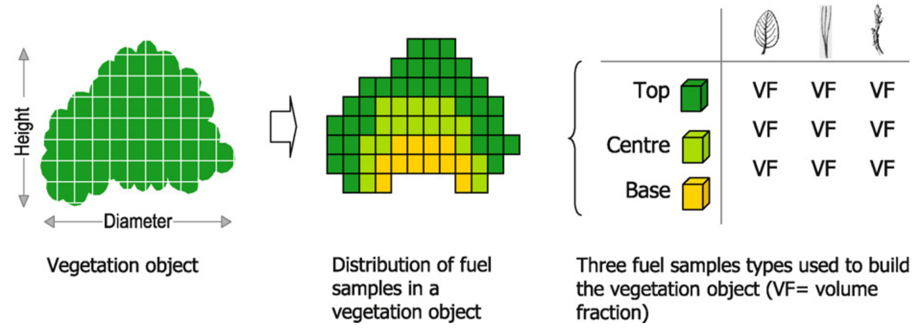


Fig. 5. A measured or virtual vegetation object built with three types of fuel sample.

approaches are possible, however, *e.g.* those that permit aggregation of the lowest units using statistical functions of heterogeneity and texture of individual strata within the vegetation.

A further development of the database could be to include a spatially explicit representation of the fuel model, in order to be able to characterise and map the fuel models over large areas. This would be possible by integrating georeferenced database such as remote sensing and GIS data.

It is envisaged that, ultimately, the database described will comprise an important part of a free-access Internet-based knowledge information system (Legg et al., 2008). The implementation of this system has started with the OODB and FuelManager application as outlined above, whilst the specification of a WIKI has also been written. This is currently being implemented by the European Forest Institute and will provide a forum for the fire community to develop an agreed standard set of terms and definitions for fire description.

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Appendix A. Information on the cube method and selected terminology

A *fuel sample* is a volume of fuel at a lower level than a vegetation object (individual plant). One or several fuel samples are necessary to build a vegetation object using the "cube method" (see below). Consequently a typical fuel sample is a 25 cm × 25 cm × 25 cm cube, although it may have other dimensions. A fuel sample may be collected by destructive field measurements, or calculated.

A *fuel plant* may be either a vegetation object corresponding to a real plant measured in the field, or a virtual plant which differs either by its shape, by the distribution of cubes within its shape, by the values of one or several fuel parameters (*e.g.* mean of several samples).

A *fuel layer* is a collection of individual plants, closely grouped and difficult to describe separately, forming a layer generally much wider than high. A fuel layer is described as a single vegetation object and has almost the same types of property as an individual plant. *Q. coccifera* shrubland is a typical fuel layer from calcareous Provence.

A.1. Cube method

The objective of cube method was to model and provide spatially explicit data about fuel load and fuel packing ratios for typical Mediterranean shrub species at the level of individual shrubs or shrub thickets (Mårell et al., 2008). Fuel packing ratio is the ratio between the fuelbed bulk density ($\mathrm{kg\,m^{-3}}$) and the fuel particle density ($\mathrm{kg\,m^{-3}}$). The cube method (Cohen et al., 2002) has been designed for modelling the spatial distribution of fuel particles within individual shrub canopies using three types of cube: (i) “top” cubes representing the outermost canopy layer typically with a large portion of photosynthetic organs, (ii) “centre” cubes representing the innermost part of the shrub canopy typically with intermediate proportions of leaves/needles and thin twigs, and (iii) “bottom” cubes representing the lower interior parts of the shrub canopy with low proportions of fine fuels relative to heavy fuels (cf. description in Morsdorf and Allgöwer, 2007). The three cube types are sampled at the top, centre and bottom of a column corresponding to the height of the shrub.

Within each cube, fuel particles are sorted in the laboratory into dead and live parts, and into size classes (leaves, needles, twigs 0–2, 2–6, 6–25 and >25 mm) for which the dry weight of each component is measured. Fuel sampling is generally carried out in elementary volumes of 25 cm side (Fig. 5). A drawing of the form of the individual shrub is made in the field or based on a set of photographs and the three types of cube are assigned within that shape. Physical, chemical and thermal properties of fuel particles not varying in space (*e.g.* surface to volume ratio, mass-to-volume ratio, ash content, density, high calorific value), are measured on individuals that have been sampled using the cube method. The dry weight of each class of fuel particles is measured for each cube and multiplied by the mass-to-volume ratio to estimate the volume fraction (packing ratio). Data may be pooled by species and by geographical region from which samples are taken.

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