Student thesis series GEM nr 04

Assessing the Potential of Embedding Vegetation Dynamics into a Fire Behaviour Model: LPJ-GUESS-FARSITE

Efrén López Blanco

2014
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Course title	Geo-information Science and Earth Observation for Environmental Modelling and Management (GEM)
Level	Master of Science (MSc)
Course duration	September 2012-June 2014
Consortium partners	University of Twente, ITC (The Netherlands) University of Lund (Sweden) University of Southampton (UK) University of Warsaw (Poland) University of Iceland (Iceland)

Assessing the potential of embedding vegetation dynamics into a fire behaviour model: LPJ-GUESS-FARSITE

by

Efrén López Blanco

Thesis submitted to the Lund University in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation

Thesis supervisors

Dr. Veiko Lehsten
Dr. Thomas Curt

ITC
UNIVERSITY OF TWENTE.
FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

LUNDS UNIVERSITET

Disclaimer

Abstract

Disturbances such as wildfires are key players involved in the shape, structure and function of the ecosystems. Fire is rarely included in Dynamic global vegetation models due to their difficulty in implementing its processes and impacts associated. Therefore, it is essential to understand the variables and processes involved in fire, and to evaluate the strengths and weaknesses before going forward in global fire modelling.

LPJ-GUESS-SPITFIRE allows the calculation of vegetation in a daily-time-step manner. However, the fire module has revealed some flaws in performance. For this reason, an alternative fire area simulator (FARSITE), a robust and semi-empirical model widely used worldwide, has been taken into account.

The aim of this study is to assess a potential embedment of vegetation dynamic (LPJ-GUESS-SPITFIRE) into spatial-explicit fire behaviour modelling (FARSITE): LPJ-GUESS-FARSITE. The study includes: (1) a comparison between simulated vegetation and observed vegetation in Mediterranean regions and, to what extent to fire recurrence affects vegetation; (2) the evaluation and comparison of fuel- and tree-related variables from the observed data, and (3) the comparison of fire behaviour performed by each model.

Simulations have shown that *Quercus coccifera* and C3 grasses are dominant at 25 years fire return interval. Besides, the fire return interval influences largely the successional stage of the vegetation. Biomass tends to increase whereas leaf area index and net primary production decrease from short to long fire recurrence periods. Dead fuel loading, fuel depth, fuel moisture 1hr and live grass, simulated in LPJ-GUESS-SPITFIRE, tend to underestimate field measurements. On contrary fuel moisture 10hr and 100hr are overestimated. Fire behaviour results from both models have underestimated field experimental results. FARSITE results, followed by LPJ-GUESS-FARSITE, have been closer related to field data than LPJ-GUESS-SPITFIRE. The results also showed evidence of more intense fires in LPJ-GUESS-FARSITE than in LPJ-GUESS-SPITFIRE, with identical input data.

This thesis concludes that both FARSITE and LPJ-GUESS-FARSITE fire behaviour’s outputs are expected to be more realistic than LPJ-GUESS-SPITFIRE. Even though results do still underestimate real observations, there is enough evidence to say that the LPJ-GUESS framework could be improved. The substitution of the SPITFIRE module by FARSITE model, together with an increase of litter and fuel loading and a decrease of fuel moisture, reflects the promising advantages in creating the meta-model LPJ-GUESS-FARSITE.

Keywords: Fire Modelling, Fire Behaviour Prediction, Dynamic Fuel Model, Fire Recurrence, Fuel Loading, Fuel Moisture, LPJ-GUESS-SPITFIRE, FARSITE, LPJ-GUESS-FARSITE, Mediterranean Ecosystem.

Acknowledgements

First of all I would like to thank my supervisor Dr. Veiko Lehsten for his guidance, advice and encouragement concerning environmental modelling. I truly appreciate the constructive and stimulating discussions. As a dummy programmer I am, each new lesson/trick shared from this unknown and fascinating world of C++ has been very welcomed.

I am also very grateful to Dr. Thomas Curt and IRSTEA who have provided me with some data and knowledge about the special conditions belonging from the study area. Undoubtedly his support, recommendations and expertise in the field has made my work better and more detailed than it would have been otherwise.

I send a special warm thank you to my family who have supported me on this motivating journey. I will forever appreciate the freedom of decision they have always granted me which has allowed me to pursue my dreams and ambitions. I would also to thanks my friends and housemates for the daily support and positives thoughts, as well as to Maria, for her helpful and invaluable suggestions regarding English grammar.

Last but not least I would like to express my gratitude to GEM programme, in special to ITC (University of Twente, NL) and Physical Geography and Ecosystem Science faculty (University of Lund, SE). The combination of a multicultural environment together with the possibility of geographical mobility and quality of education have made this experience enriching and fulfilling.

Table of Contents

Abstract v
Acknowledgements vi
Table of Contents vii
List of figures ix
List of tables x
List of equations xi
Abbreviations xii
1. Introduction 1
  1.1 Problem statement 2
  1.2 Aim and objectives 4
2. Background 7
  2.1. Control factors: a matter of scale 7
  2.2. Fire behaviour 8
  2.3. Fire recurrence 12
  2.4. Fuel 12
    2.4.1. Fuels characteristics 13
    2.4.2. Fuel moisture 14
  2.5. Basic parameterization in fire modelling 16
    2.4.3. Fuels models 16
    2.4.4. Rate of spread 18
    2.4.5. Fire intensity 19
    2.4.6. Byram’s fire-line intensity, flame length and heat per area... 20
  2.5. What should a fire model embedded in a DGVM consider? 21
3. Methodology 23
  3.1. Study area 23
  3.2. Fire behaviour models 25
    3.2.1. LPJ-GUESS-SPITFIRE 25
    3.2.2. FARSITE 26
    3.2.3. LPJ-GUESS-FARSITE 30
  3.3. Model’s set up 31
    3.3.1. Assessing the variable and parameters selection from LPJ-GUESS-SPITFIRE 31
    3.3.2. Assessing initializers parameters at which LPJ-GUESS-SPITFIRE needs to be run 33
    3.3.3. Code’s implementation in LPJ-GUESS-SPITFIRE 35
    3.3.4. Code’s modification in LPJ-GUESS-SPITFIRE. 37
    3.3.5. Assessing parameters at which FARSITE needs to be run..... 38
  3.4. Introducing LPJ-GUESS outputs as inputs in FARSITE: LPJ-GUESS-FARSITE’s germ 40
  3.5. Model’s comparison: data analysis 43
4. Results 47
  4.1. Models’ set up 47
    4.1.1. Assessing initial parameters at which LPJ needs to be run.... 47
    4.1.2. Code modification in LPJ-GUESS-SPITFIRE 51
  4.2. Comparison between models: LPJ-GUESS-SPITFIRE vs FARSITE.. 54
    4.2.1. Fuel and tree-related characteristics 54
    4.2.2. Fire behaviour performance 57

4.3. Introducing LPJ-GUESS outputs as inputs in FARSITE: LPJ-GUESS-FARSITE's germ 61
5. Discussion 65
5.1. Model's set up 65
5.1.1. Assessing initializers parameters at which LPJ needs to be run 65
5.1.2. Code's modification in LPJ-GUESS-SPITFIRE: the before and the after 70
5.2. Comparison between models 71
5.2.1. Fuel and tree-related characteristics 71
5.2.2. Fire behaviour parameters 77
5.3. Recommendations 82
6. Conclusion 85
7. Annexes 87
7.1. Additional equations of fire spread. 87
7.2. Additional formulation describing elliptic spread's shape. 88
7.3. Main characteristics of the fuel types for the Provence region (Curt et al. 2013). 89
7.4. PFT characterized in LPJ-GUESS (2008 version). PFT present in Provence region (5º23' E 43º2' N). 90
7.5. Input data requirements for FARSITE v4.1 91
7.6. Variable selection from LPJ-GUESS-SPITFIRE to FARSITE. 94
7.7. LPJ-GUESS-SPITFIRE code's implementation 96
7.8. LPJ-GUESS-SPITFIRE code's modification 103
7.9. Synthetic landscape's creation from LPJ-GUESS-SPITFIRE through MATLAB code 104
7.10. Fuel-related variables in a 30 years' time series 105
7.11. Synthetic landscape based on 9 patch custom fuel model 106
7.12. Observed vs simulated ROS measurements in Sardinia, Italy (Salis 2007). 107
7.13. Examples of fire behaviour. From Albini F.A unpublished training notes (Pyne et al. (1996) 108
7.14. Scripts used in digital format. 109
8. List of references 111
9. List of published master thesis 123

List of figures

Figure 1. Fire Fundamentals Triangle (1) and Fire Environment Triangle (2) redrawn from Pyne et al. (1996) 7
Figure 2. Fire model from FCFDG (1992) 9
Figure 3. Elliptical rate of spread´s shape. Based on FCFDG 1992 and FARSITE's technical documents 10
Figure 4. Vertical vs horizontal orientation based on fuel depth-fuel load relation according to Anderson (1982). 14
Figure 5. Graph of fuel moisture content over 3 time-lags of dead fuel in FARSITE 15
Figure 6. Framework description of the important component a coupling fire model-DVGM should include. By Thonicke et al. (2010) based on Fosberg et al. (1999) 22
Figure 7. Aix-en-Provence 43°22N 05°27E 24
Figure 8. Landscape file generation (.LCP) in Provence region 29
Figure 9. Conceptual diagram LPJ-GUESS-FARSITE. 30
Figure 10. Synthetic landscape, from LPJ-GUESS-SPITFIRE into FARSITE 41
Figure 11. CMASS, NPP and LAI within 10, 20 and 30 years fix fire return interval 48
Figure 12. CMASS, NPP and LAI within 40, 50 and 60 years fix fire return interval 49
Figure 13. Boxplots: Code's modification in LPJ-GUESS-SPITFIRE 52
Figure 14. Histograms: ROS, FLI, FML, IR and HPA performance due to code's modification in LPJ-GUESS-SPITFIRE 53
Figure 15. Boxplots: LPJ-GUESS-SPITFIRE vs FARSITE 58
Figure 16. Histograms: ROS, FLI, FML, IR and HPA performance LPJ-GUESS-SPITFIRE vs FARSITE 60
Figure 17. Boxplots: LPJ-GUESS-SPITFIRE vs FARSITE vs LPJ-GUESS-FARSITE 62
Figure 18. Histograms: ROS, FLI, FML, IR and HPA performance LPJ-GUESS-SPITFIRE vs FARSITE vs LPJ-GUESS-FARSITE 63
Figure 19. Succession stage dependent of fire recurrence (Schaffhauser et al. 2011) 67
Figure 20. Hazard of burning at Maures massif (Curt et al. 2013) 69
Figure 21. Huygens´ principle for a steady wind (V) 88
Figure 22. Canopy cover, fuel depth, Mx, fuel loading and fuel moisture mean values over 30 years' time series 105
Figure 23. Boxplots: LPJ-GUESS-FARSITE simulations based on 9 custom fuel models 106

List of tables

Table 1. Input variable and parameter into Rothermel’s fire model 17
Table 2. Fire Intensity-related equations 20
Table 3. Wilcoxon Mann-Whitney Test: Code's modification in LPJ-GUESS-SPITFIRE 51
Table 4. Custom fuel model collected from Provence region......................56
Table 5. Custom fuel model generated by LPJ-GUESS-SPITFIRE................56
Table 6. Tree-related variables comparison 56
Table 7. Wilcoxon Mann-Whitney Test: LPJ-GUESS-SPITFIRE vs FARSITE....57
Table 8. Comparison of conditions during simulations and the field experiments 80
Table 9. Additional equations of fire spread from Rothermel (1972)...........87
Table 10. Additional formulation of wind effect from Anderson (1982) 88
Table 11. Main characteristics of the fuel types in limestone-derived soils. Provence area 89
Table 12. Main characteristics of the fuel types in acidic-derived soils. Provence area 89
Table 13. PFT present in Provence...90
Table 14. Input data requirements in FARSITE..91
Table 15. Variable selection from LPJ-GUESS-SPITFIRE............................94
Table 16. Custom fuel model of 9 patches 106
Table 17. Observed vs Simulated ROS 107
Table 18. Examples of Rate of Spread 108
Table 19. Examples of Reaction intensity 108
Table 20. Flame length and Fire-line intensity related to fire suppression activities 108

List of equations

Equation 1. Rate of Spread (Frandsen 1971) 18
Equation 2. Rate of Spread (Rothermel 1972)..18
Equation 3. Reaction Intensity (Rothermel 1972) 19
Equation 4. Byram’s fire line Intensity (Byram 1959)................................20
Equation 5. Flame depth (Andrews 1986)..20
Equation 6. Heat per area (Andrews 1986)..20
Equation 7. Flame residence (Andrews 1986) 20
Equation 8. Flame length (Andrews 1986)..20

Abbreviations

The models:

LPJ- Lund & Potsdam & Jena
DGVM- Dynamic Global Vegetation Model
GUESS- General Ecosystem Simulator
SPITFIRE- Spread and Intensity of Fire
FARSITE- Fire Area Simulator

The fire behaviour-related variables:

ROS- Rate of Spread
IR- Reaction of intensity
FLI-Fire line intensity
FML-Flame length
HPA-Heat per area

The institution:

IRSTEA- Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture

1. Introduction

Land biosphere plays a vital role on the global carbon cycle, the climate system and it is an important part of global vegetation's shaping (Prentice et al. 2001). In the biosphere, complex mechanisms and processes perform at multiple inter-related spatio-temporal scales. These processes interact most of the time between them all, allowing feedback loops effects without clear and visible consequences. In System Earth everything is connected (Dopheide et al. 2012). An example of such kind of processes are natural disturbances. Even though disturbances impact over the system's balance, they are simultaneously an intrinsic part of the ecosystems, which means that it is a factor needed for the preservation of many cyclic natural structures (Prentice et al. 2007).

Fire is one of the primary global disturbance factors in all terrestrial ecosystems (excluding the polar and desert biome), including soil and litter, disrupting its structure and composition (Pyne et al. 1996). It also has a large-scale relation with the climate conditions and has effects on carbon storage or biochemical cycles (Thonicke et al. 2001). Annual global carbon emissions (from biomass burning) make a substantial contribution into the tropospheric carbon budget, estimated in a range from about 1.7 to 2.5 PgC (Thonicke et al. 2010). Since ignition, fuel composition and dryness are the main control factors of fire at local level, both climate and vegetation dynamic are closely interconnected with the fire performance and its effects (Bowman et al. 2009).

The increasing number of evidences about a potential speed up of the global warming (Houghton et al. 2001) has generated a demand for tools that can predict the risks of dramatic environmental changes. (Prentice et al. 2007). This request can be partly satisfied by environmental modelling and it became an important research pathway, facilitated at the same time by technological improvement. Since the 70s, there was a need for a better understanding and quantification of different control factors as well as interrelation between processes, causes and consequences of wildfires within Earth system dynamics (Bowman et al. 2009). Such kind of task can be addressed by process-based models validated either through field data and/or satellite imagery. A potential extrapolation of results into speculative "what if…?" future scenarios provide modelling approaches with an extra motivation.

1.1 Problem statement

When modelling a fire behaviour, different approaches have been attempted depending on the spatial scale: from methods concerning fine spatial resolution, focusing on local and well-defined conditions, to studies involving coarse resolution. The state-of-the-art of worldwide terrestrial biosphere models, which represent vegetation dynamics as well as biochemical process, are represented by Dynamic global vegetation models (DGVMs) (Cramer et al. 2001; Smith et al. 2001; Thonicke et al. 2001; Sitch et al. 2003; Arora and Boer 2005; Prentice et al. 2007; Li et al. 2012). Fire modules have been embedded in these models testing fire spread and intensity simulations together with fire-vegetation interaction and post-fire mortality (Thonicke et al. 2010), spatio-temporal fire regimes (Venevsky et al. 2002; Lehsten et al. 2010), fire-climate feedbacks (Archibald et al. 2010) as well as biomass burning emissions (Lehsten et al. 2009; Thonicke et al. 2010).

Although the models' performance has enhanced fire phenomena characterization along the last decade, unavoidable limitations have been detected by the simple fact that models are simplifications of what occurs in reality. Glob-FIRM (Thonicke et al. 2001) allowed fractional burnt performance in grid cell basis, depending only on the length of the fire season and fuel loading. On the other hand it neglects any characterization of ignition source as well as the wind's influence over the rate of spread. The model also disregards an incomplete combustion of plants, i.e. assumes a constant fire-induced mortality rate for each plant functional type (PFT). Reg-FIRM (Venevsky et al. 2002) integrated a climatic fire danger, fire ignition source and explicit model rate of spread. It does not measure any trace gasses and aerosol emissions. Similar to Glob-FIRM, fire-induced effects over the vegetation remain absent. MC-FIRE embedded in MC1 DGVM (Lenihan et al. 1998) incorporated a novel post-fire mortality computation according to Cohen and Deeming (1985) even though unrealistically only allows one ignition per grid cell per year. CTEM-FIRE (Arora and Boer 2005) presented a simulation model of fire activity and novel biomass burning emissions. Fire-induced consumption of biomass and plant mortality is prescribed independent of fire intensity. Litter and litter moisture were not included explicitly.

Due to the ongoing improvement of computer's performance, a further twist concerning modelling calculations became affordable, significantly increasing the computational-complexity environments. Proof of this progress is the fire module SPITFIRE, which has been embedded into LPJ-DVGM (Thonicke et al. 2010), into LPJ-GUESS (Lehsten et al. 2009) and finally into LPX (Prentice et al. 2011). The model performs computations in coarse spatial resolution, 0.5° grid. It distinguishes different dead and live fuel classes, fuel loads as well as moisture ratios. The basic physical properties and processes determining fire spread and intensity were taken from Rothermel (1972) applying some modifications. It also implements formulation about fire-effect on vegetation as a function of structural plant properties as well as trace gases and aerosol emissions (Thonicke et al. 2010). LPJ-SPITFIRE framework presents at the same time a number of limitations such as (1) does not take into account slope, despite this being an important parameter concerning fire spread, (2) some input variables are directly prescribed from literature (which in certain conditions derivate in peculiar results), (3) overestimation of burnt areas in some regions and underestimations in others (4) does not characterize more than 1 day fire performance, (5) flaws in fuel moisture calculations and therefore (6) unrealistic modelling of rate of spread (most likely in grasses) . Improvements on the model have been described by Pfeiffer and Kaplan (2012).

On the other hand, up-to-date modelling techniques at lower scale follows a slightly different procedure (Albini 1976a; Albini 1979; Andrews 1986; Scott and Reinhardt 2001; Finney 2004; Scott and Burgan 2005). Although local fire behaviour models are based on the same parameterization principles as those followed by fire modules embedded in DVGM, the level of detail extensively changes. This kind of models allows fire modelling at relative fine scale (i.e. local, 1 km or even less). An explicit spatial component is typically included, facilitating the interoperability with GIS software packages. It also includes processes topography-dependent lateral fire spread which deepens more into a realistic representation. Fire behaviour such as crowning, torching and spotting could have been successfully implemented. FARSITE (Fire Area Simulator), developed by USDA Forest Service, is a fire growth simulator which has been widely utilized as well as evaluated at different ecosystems all over the world. It can spatially and temporally compute fire spread, intensity or different post-frontal fire behaviours such as carbon biomass emissions. The outputs are more reliable and accurate than the ones from coarse scale.

Additionally to field measurements, Salis (2007) attempted the validation of simulated rate of spread (ROS) in North Sardinia along four different locations, each of them with different conditions. A table enclosed in Annexe 7.12 reproduce the most important characteristics reported, such as dominant species, plant height, temperatures or wind as well as the observed and the simulated ROS. The author has simulated ROS up to 11 m/min under relative high wind speed conditions. The results accurately match measured field observations. Salis proposed two important interpretations from these results: (1) as long as an accurate custom fuel model is developed together with a precise wind's dataset for a region with specific conditions such as Mediterranean basin, then (2) FARSTE allows very precise and accurate fire behaviour simulations

Embedding FARSITE into LPJ-GUESS for this purpose seems to be suitable because: (1) LPJ-GUESS can simulate vegetation-related inputs: (dynamic) fuel composition, fuel loading and fuel moisture (2) the results from FARSITE can be approximated by a mathematical model for predicting fire spread in equations, (3) it allows the same assumption about elliptical spread shape and (4) both models follow the Huygen's principle involved in fire growth computation.

1.2 Aim and objectives

To simulate the effect of fire on the dynamic vegetation at a fine scale, I will attempt the assessment of a potential fire meta-model running into the modular framework of Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) (Smith et al. 2001).The main aim of this Master thesis is to evaluate the potentials from embedding vegetation dynamic (LPJ-GUESS-SPITFIRE) into a spatial-explicit fire behaviour model (FARSITE): LPJ-GUESS-FARSITE. The research took a local perspective supported by field data in order to establish a robust starting point. Understanding how fire performs in a local scale would most likely allow fire behaviour upscaling in future, before focussing on coarse resolution directly. The case study area is centred on the Maures massif, a characteristic landscape located in Provence (France).

Since flaws in performance and lacks in relevant input variables directly influencing fire behaviour were reported, the hypothesis for this thesis is that both FARSITE and LPJ-GUESS-FARSITE outputs are expected to be more realistic than LPJ-GUESS-SPITFIRE output. The null hypothesis establishes no significant difference between LPJ-GUESS-SPITFIRE, FARSITE and LPJ-GUESS-FARSITE outputs.

In order to do so, the main research questions addressed in this research are:

RQ 1	Does LPJ-GUESS-SPITFIRE represent the actual vegetation from Provence? Does the fire return interval influence ecosystem succession in a realistic manner (in comparison to field measurements) in the study area?
RQ 2	Does LPJ-GUESS-SPITFIRE get similar fuel- and tree-related estimations from vegetation in comparison with data collected on the field along the study area?
RQ 3	Does the existing LPJ-GUESS-SPITFIRE model represent realistic and accurate fire spread as well as fire intensity?
RQ 4	Does LPJ-GUESS-FARSITE represent realistic and accurate rate of spread as well as fire intensity?
RQ 5	Does LPJ-GUESS-FARSITE perform better fire behaviour than LPJ-GUESS-SPITFIRE? Can the estimations be improved?

In order to answer these questions, the following steps will be required:

- Assessing variable selection and its range at which FARSITE needs to be run.
- Assessing initializers parameters at which LPJ-GUESS-SPITFIRE needs to be run.
- LPJ-GUESS-SPITFIRE's code implementation.
- Simulation of the typical LPJ-GUESS conditions for the cases study area.
- Running FARSITE for the range of conditions in LPJ-GUESS-SPITFIRE.
- Comparison of the results from LPJ-GUESS-FARSITE with the results from LPJ-GUESS-SPITFIRE.
- Evaluation of both FARSITE and LPJ-GUESS-SPITFIRE estimations for a number of sample fires.

In the first chapter some background information about wildfires, control factors, characteristic fire behaviour, fire recurrence and its relationship with the vegetation, description of burnable fuel and basic modelling parameterization are given. In chapter 3, the study area and the models used are presented, followed by the methodology used in this thesis. The results are presented in chapter 4 and discussed in the subsequent chapter 5. In the final chapter, a conclusion for the main research questions are given. A set of annexes are enclosed supporting concepts, ideas as well as adding extra information.

2. Background

In order to address properly the fire behaviour modelling, it is required first of all to understand what control factors are behind fire performance: the processes concerning the physical and chemical fundamentals, on the one hand; and the behaviour itself, derived from the environment, on the other. Finally an interpretation of the theoretical background translated into fire model parameterization, a short review of the most important variables and parameters involved as well as an overview of what a good fire behaviour model should include are presented.

2.1. Control factors: a matter of scale

A phenomenon such as forest fire disturbance requires a different point of view depending on the assessment of the event in local or regional scale. Fire forcing drivers vary in spatial scale, but also temporally due to short/long-term time-series regimes.

For instance, in a local-based perspective, suitable fuel, enough dryness and an ignition's source are the basic conditions required for a fire event (Figure 1, dark-grey triangle (1)). These are known as the major factors of fire fundamentals illustrated within the "Fire Fundamentals Triangle" (Pyne et al. 1996). Fuel refers to flammable material including particle's type, composition, density and moisture content. Dryness takes into account state of fuel related with weather conditions. On the other hand, ignition refers to the source heat necessary to reach ignition points as well as the heat release, which should be enough to sustain combustion (Pyne et al. 1996). The case of absence of one of these three factors the triangle does not work anymore and the fire does not occur.

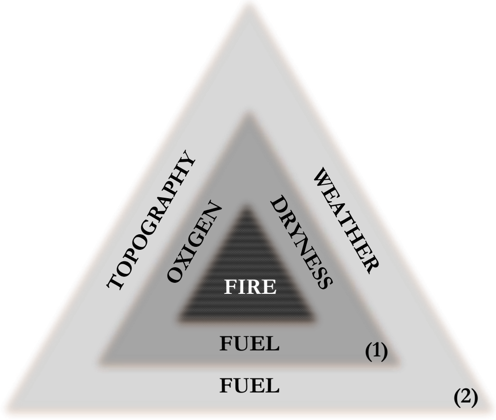


Figure 1. Fire Fundamentals Triangle (1) and Fire Environment Triangle (2) redrawn from Pyne et al. (1996)

When up-scaling from local perception into landscape-based level, the fire behaviour is defined by weather, topography and fuel (Figure 1, light-grey triangle (2)). The three of them are the main drivers behind the "Fire Environment Triangle" (Pyne et al. 1996). The interaction of these factors and with the fire itself will define the fire behaviour. Topography refers directly to slope, aspect and elevation although it also can indirectly influence fuel and weather characteristics. Fuel is a critical factor within fire behaviour and it depends on, among other things, fuel size, fuel dead/live composition and moisture (Fuel models are reviewed more in detail at point 2.4). Weather variables such as temperature, precipitation, relative humidity and wind (this latter has great impact over fire spread) influence fire ignition as well as the fuel state.

In order to understand properly the "rich picture" about main drivers involving global-based wildfires, an extra triangle is required. The extension would depend on vegetation, climate and land use (Bowman et al. 2009), being the latter triangle beyond the scope of this research. This framework helps to put cause-effect feedbacks between the vegetation dynamics' state, influence of environmental conditions and wildfires' impacts estimation along the system in context.

2.2. Fire behaviour

Wildfire dynamics go through several stages ranging from pre-ignition, ignition, combustion and extinction. First of all an ignition is needed in the form of heat supply for fuel available in the surroundings. Dehydration, pyrolysis and release of gases follow the process. If the gases emission from fuel are suitable, it ignites a flame and the fire has the possibility to spread to a different location (Rothermel 1972). Combustion occurs when fire spreads either in form of flaming or smouldering, releasing heat in form of exothermic reaction. If not enough heat or source of heat is longer available, the extinction of the fire occurs.

Wildfires can be started by natural or anthropogenic events. Lightning strikes are the main natural ignition sources. Land (field) management activities such as agriculture or forestry, discarded cigarettes or high-power-lines are examples of man-made sources. Spontaneous ignition has also been observed as consequence of internal heating in hay, chip and sawdust's pile (Pyne et al. 1996; Johnson and Miyanishi 2001). The stochastic nature of fire disturbance significantly increases the difficulty of fire behaviour modelling (Prentice et al. 2007).

In general there is a single source point from where the fire spreads. Two different states representing fire growth after the ignition episode can be characterized: acceleration (also called build-up) and quasi-steady-state time (Chandler et al. 1983; Pyne et al. 1996). The acceleration time represents the period of time from ignition until fire reaches the equilibrium state. Reached this stage, fire has a constant forward speed, i.e. steady rate of spread (Rothermel 1972). A fire acceleration model for open canopy by the Canadian Forest Fire Prediction System is shown in Figure 2.

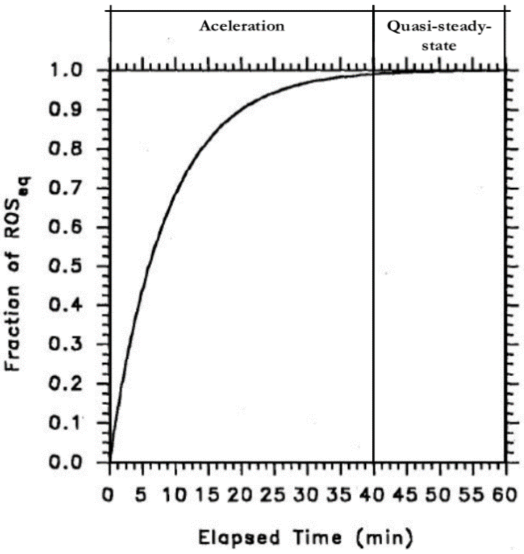


Figure 2. Fire model from FCFDG (1992)

A fire growing event from a point of ignition to each point of the fire front will evolve an elliptic shape of spread assuming moderate wind effect as well as homogenous fuel and weather conditions (Weber 2001). The elliptical representation, widely used in literature (Rothermel 1972; Andrews 1986; FCFDG 1992; Finney 2004; Thonicke et al. 2010; Pfeiffer and Kaplan 2012), can be used to characterize the shape of fire from the point source in such a way that: (1) higher length-to-width ratio in increasing slopes and in the direction of wind (i.e. faster fire spread), (2) front-back-flank represent respectively the fastest, slowest and intermediate spreading part of the fire and (3) the more homogenous conditions (for instance fuel, wind or slope) the less irregular elliptical shape. These three behaviour patterns are represented in Figure 3.

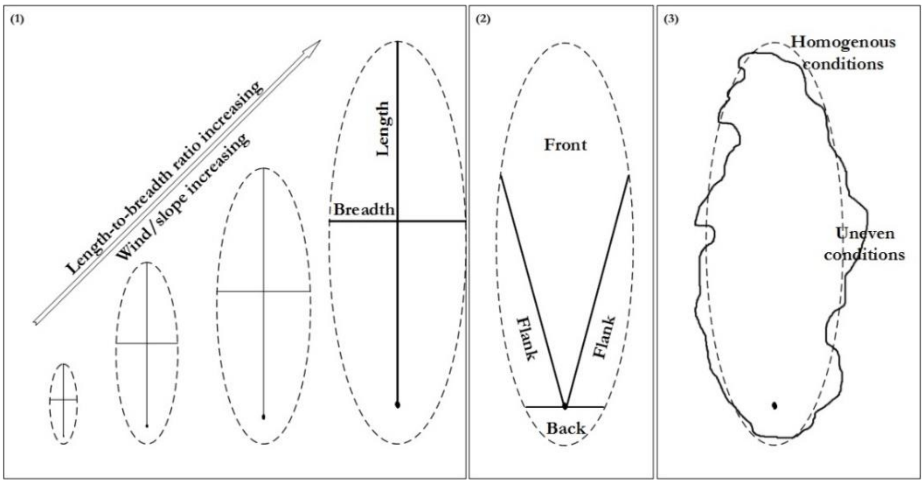


Figure 3. Elliptical rate of spread´s shape. Based on FCFDG 1992 and FARSITE's technical documents

Three different types of fire can be well-defined conditional upon what kind of fuel is available for combustion: ground, surface and crown fires. Ground fires typically burn material underneath the superficial layer. Duff, which has high organic carbon content, exemplifies a kind of peat land liable to post-frontal combustion. Surface fires perform at the superficial level burning grasses, shrubs, dead branches, forest needles or leaf-sapwood-heartwood litter. Classical fire modelling was first performed experimentally in the 70s based on this fire class. Crown fires have typically got up from the ground and burnt either tree or/and shrubs canopies. Crown fires can derive into extreme fire behaviour such as torching or spotting increasing fire intensity and the impacts carried out. Torching refers to the sudden canopy ignition from surface due to the intensity, whereas those new fire spots are originated beyond fire-line as consequence of firebrands fliers caused by spotting (Chandler et al. 1983; Pyne et al. 1996).

In order to acquire a meaningful understanding about fire behaviour, three concepts need to be introduced. The desire to address suppression and management of natural resources during fire events as well as assessment of fire effect over plant communities (Johnson and Miyanishi 2001) established fire characterization of rate of spread (ROS) together with fire intensity and post-frontal combustion (i.e. burning emissions).

ROS refers to the speed (average m/min) at which the fastest section of the fire perimeter, also called fire-line, spreads into unburnt fuels, following the perpendicular direction to the perimeter. Fluctuating conditions can easily alter the spread rate. Wind and slope are sensitive variables affecting ROS behaviour and it depends on direction and magnitude. Fires tend to fast-spread at up-slopes as well as in the wind direction although it is also possible downhill due to combined wind effect. Likewise fuel characteristic is a critical variable involving fire spread. For example fine dead material such as grass, leaf or needle litter burns faster than heavy trunks or duff, which can remain smouldering afterwards the fire-line passed (Pyne et al. 1996).

The fire intensity, following the United States fire behaviour prediction system, can be measured by flame length, fire-line intensity, reaction intensity and heat per unit area (Andrews 1986). Fire-line intensity, also called Byram's intensity (FLI), is the heat released per unit of time per front-rear distance of the flaming zone (kW/m), called flame depth (Byram 1959). Reaction intensity (IR) refers to heat released per area per time unit in the flaming zone (kW/m2). Heat per unit area (HPA) account for the heat emitted per area during whole flaming event (kJ/m2). Flame length (FML) is the distance between the average flame front to the middle of the flaming zone (m) (Pyne et al. 1996; Alexander and Cruz 2012).

Typical examples of fire intensity together with rate of spread prescribed by Albini F.A (unpublished training notes reported in Pyne et al. (1996)) are enclosed in the annexe 7.4. The units were conveniently transformed from English to Metric units. In a like manner, fire behaviour has been characterized through laboratory and field measurements (Cheney and Gould 1995; Morandini et al. 2005; Morandini et al. 2006; Santoni et al. 2006; Silvani and Morandini 2009; Curt et al. 2010; Curt et al. 2011; Ganteaume et al. 2011; Silvani et al. 2012). This valuable information can be used as a guideline for fire model's validation.

Even though the fire front has long passed, active processes still can remain active. If soils with high organic composition are available, potential smouldering combustion could occur for days, months or even years. Decomposed plants with low concentration of cellulose and higher concentration in lignin favour the process. Likewise post-frontal combustion burns woody surface fuels and litter. Fuel closely packed such as woody debris are more likely to smoulder rather than fine litter (Pyne et al. 1996). Fuel composition in these conditions tends to release great flux from burning emissions. As rule of thumb:

the dryer the fuel and the more oxygen is available, the more CO2 is produced; and the wetter and less oxygen is available, the higher the ratio of trace gases like methane, CO or VOCs is (Lehsten 2013). Lastly, the feedbacks loop prediction between fire and climate became a crucial matter (Rothermel 1991; Lehsten et al. 2009; Thonicke et al. 2010). Understanding how relevant the fire contribution into the system is, allows speculations about what could be derived in future scenarios.

2.3. Fire recurrence

According to Gill (1979), the fire regime is characterized by the association of the fire spatial pattern as well as the fire intensity, the fire seasonality and the fire recurrence, all of them befalling an specific target area. The fire recurrence itself represents the temporal quantification of how often the area is affected by the impact of a fire. At the same time, fire recurrence can be divided into both (1) fire frequency, standing for the number of fire events taking place within a specific area during a specific period of time (Eugenio et al. 2006); and (2) fire return interval, which represents the period of time in between two successive fires (Schaffhauser et al. 2011).

The fire return interval plays an important role over the response experienced by plants and ecosystems due to fire disturbance. As said by Malamud and Turcotte (1999), wildfires and vegetation are most likely to establish positive feedback loops in between of them. For instance, fire can affect the structure and composition of the vegetation, which, at the same time, affects behaviour of future disturbance events. The plant regeneration capacity, also called post-fire resilience, establishes two well defined kind of plant adaptation facing wildfires: resprouters species (characteristic from long fire recurrence) versus seeders species (typically found within large fire return intervals) (Pausas 1999; Acácio et al. 2009; Curt et al. 2009; Schaffhauser et al. 2012b).

2.4. Fuel

According to Paysen et al. (2000) available fuel refers to the amount of either dead or living biomass that burns under a given set of conditions. Fire dynamics is dependent on the fuel availability whilst fuel moisture is strongly dependent on environmental conditions. Once fuel is ignited, litter fuel can expand both in horizontal and vertical direction (Plucinski and Anderson 2008). As fire fundamentals and environmental triangles illustrated at point 2.1, the fuel component is present in both local and landscape-based scenario, playing a crucial role. Fuels affects either how easily a fire ignites, its rate of spread, its intensity or the burning emissions (Rothermel 1972; Andrews 1986; Scott and Burgan 2005).

Following Pyne et al. (1996) fuels can be classified based on its type, its state or its size (diameter). Fuel type describes the fuel itself and the physical properties related to fire. Fuel state takes into account environmental conditions such as the moisture content.

2.4.1. Fuels characteristics

Quantity, size and shape, compactness and arrangement (Chandler et al. 1983; Pyne et al. 1996) are the most common physical properties in regards to fuel. Fuel loading is the amount of both aboveground dead and living fuel to be found. It is quantified by measurements of fuel's oven-dry weight per area (T/ha). Measuring oven-dry weight allows the independent categorization of moisture's parameter. Size gives an idea about how fine or coarse the fuel's target is and usually is defined by surface-area-to-volume (SAV) ratio. The higher the SAV ratio, the finer the fuel is, hence the easier to ignite. It relates directly to ignition time and ROS. Compactness relates to the space in between fuel particles. Nevertheless fuel bulk density is the most common way of representing the fuel porosity, i.e. fuel weight divided by volume. It directly affects ignition time as well as how combustion performs. Finally, arrangement establishes a criterion for fuel orientation (horizontal vs vertical) together with its spatial distribution, level of mixture and live-to-dead ratio. In Figure 4 different fuel groups are oriented in two basic directions depending on relation fuel depth-fuel load: vertically, as in grasses and shrubs, and horizontally, as in timber, litter, and slash (Anderson 1982).

Barrows (1951) categorized fuel into ground, surface and crown classes according to vertical strata. The ground material is mostly composed by roots and duff. Superficial fuel includes small trees and shrubs, forest litter and fallen wood, grasses and litter formed by fallen leaves, twigs, needles, steams and bark. Crown fuel refers specifically to large shrubs and canopy (stand height) trees. A combination of different layers are defined as fuel complexes (Scott and Burgan 2005). The classification proposed establishes an inflexion point for the separation of surface fire spread computation

(Rothermel 1972) and crown based phenomena (Scott and Reinhardt 2001).

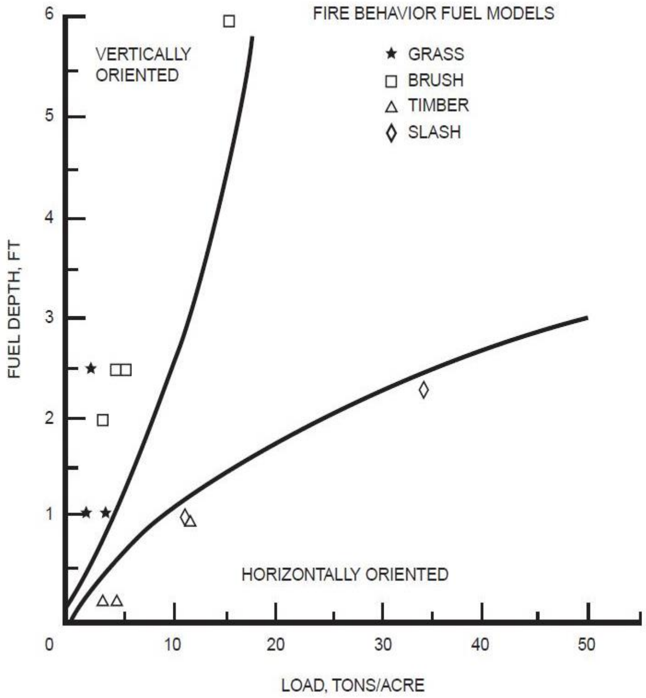


Figure 4. Vertical vs horizontal orientation based on fuel depth-fuel load relation according to Anderson (1982).

2.4.2. Fuel moisture

Fuel moisture, dependent on environmental conditions, strongly regulates both dead and living material available for combustion. Water is evaporated before the fuel could be heated up to the temperature required for ignition. For this reason a low degree of humidity can be derived into greater facility for pre-heating and ignition, acceleration of combustion and higher fire spread and intensity. Hence fuel moisture affects important aspects of fire behaviour such as ROS, intensity, smoke production, fuel consumption and plant mortality (Pyne et al. 1996).

According to Fujioka et al. (2008) fuel moisture is derived as "the mass of water present in the fuel". It is generally expressed as fraction of water mass (i.e. initial fuel mass minus dry mass) divided by the oven-dry fuel mass. The percentages can widely vary depending on whether dead fuel (from 1 or 2% in deserts to 30% due to fibre saturation or even up to 300% on decayed woody) or live fuel (ranging from 50% up to 1000% because of duff) are present.

Dead fuel moisture is influenced mainly by environmental factors such air temperature, relative (air) humidity, solar radiation and rainfall. These are dependent on local topographic and site factors like elevation, slope, aspect, canopy cover, fuel composition and fuel size (Finney 2004). On the other hand, as noted by Rothermel (1983), live fuel moisture is a function of the physiological processes occurred in the plants. Moisture content is influenced by factors such us seasonality, precipitations, temperature or the plant species themselves. Dead fuel size can be classified based on the response to environmental changes by moving its moisture to a new equilibrium. Fuel diameters have been matched according to their "time lag". Time lag is defined as the time period required for a dead fuel to respond within 63.2% of the new equilibrium moisture content (Missoula Fire Science Laboratory 2010). This means that thinner diameters have lower time lags, hence a faster response to changes in the environmental conditions than thicker fuel sizes. This can be observed in Figure 5. Time lag categories used for fire behaviour were specified as 1hr (leaves and twigs), 10hr (small branches), 100hr (large branches) and 1000hr (boles and trunks).At the same time these categories represent the size classes: 0-.635cm, 0.635-2.54cm, 2.54-7.62cm and 7.62-20.32cm respectively (Andrews 1986). Even though it is an oversimplification, this terminology is still used (Finney 2004; Thonicke et al. 2010; Pfeiffer and Kaplan 2012).

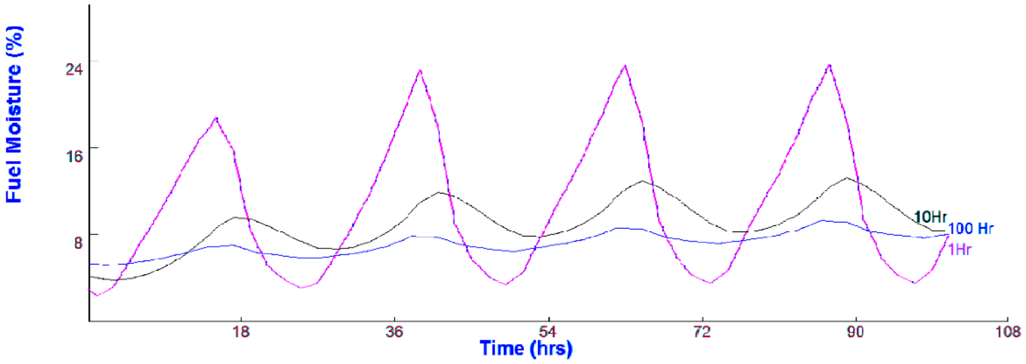


Figure 5. Graph of fuel moisture content over 3 time-lags of dead fuel in FARSITE

2.5. Basic parameterization in fire modelling

Generally speaking, there are three different methods which can predict fire behaviour. These are empirical, statistical and theoretical (Chandler et al. 1983). Empirical models require large fires dataset where all parameters except one are constant in order to evaluate the effect over ROS and IR. The main disadvantage of this approach is the interaction effect between variables, as it has a tendency to be overlooked. Statistical methods are supported by variants of classical multiple-regressions models. Although it provides confidence limits about the ROS prediction, either non-linear relation between variables nor compulsory entire calculation when new data are included make this methodology challenging.

The theoretical models are based on physical and thermo-dynamical principles. The advantage of these models are the use of well-known and verified relationships allowing up-scaling, hence the validation process is easier and dataset requirements are reduced in comparison to other approaches (Chandler et al. 1983). This thesis presents work related with the theoretical (process-based) model.

2.4.3. Fuels models

Mathematical fire behaviour models such as Rothermel (1972) require a specific and detailed fuel description. Since the fire model is a set of equations, the fuel model is characterised by a specific set of fuel-bed inputs fitting into the parameterization. It is essential for ROS, fire intensity and burning emission computations (Pyne et al. 1996). Fuel models are tools which simply help the user to realistically estimate fire behaviour (Anderson 1982; Scott and Burgan 2005). In Behave and FARSITE there are two different kinds of fuel models:

- Static fuel models: aiming at fire spread prediction.
- Dynamic fuel models: pointing at fire danger rating system (NFDRS) but beyond the scope of the present study.

Although fuel models try to reduce the complexity within fire modelling, it is challenging to adequately characterize heterogeneous complexes (reviewed at point 2.3.1), where large differences in physical properties such as surface-to-volume ratio or fuel height can diverge greatly.

One of the first attempts at establishing a fire behaviour fuel model was Rothermel (1972) over his fire spread prediction model. He took into account 11 different fuel types. The fuel models were defined by fuel loading by size class (Tons/Ha), fuel depth (m) and fuel particle size (fine, medium, large). Particle density, heat content, total / effective mineral content and moisture of extinction were constant-defined. Albini (1976a) improved those 11 fuel models adding two more (11+2) and reclassified both within 4 groups: grass- , shrub- , timber- and slash-dominated. At the same time a specific moisture of extinction, referring to moisture content at which fire will not spread (Rothermel 1972), for each fuel type was defined. The previous set of constants remain without changes. BEHAVE (U.S.) fire behaviour prediction developed by Anderson et al. (1982) defined fuel models by vegetation types with specific heat content as well as specific packing ratios for each fuel. FARSITE (Finney 2004) allowed dead/live fuel differentiation in order to improve the accuracy of the computations. Scott and Burgan (2005) refined the whole fuel model developed until the date implementing up to 40 standard fire behaviour fuel models. The required fuel input variable and parameter selection for Rothermel's fire model is presented below, Table 1.

Symbol	Variables	(metric) unit
w	Fuel loading: dead fuel (w_{1hr},w_{10hr}, w_{100hr}) & living fuel (w_{herb},w_{woody})	Tons/Ha
σ	Surface-to-volume ratio: dead fuel (σ_{1hr}) & living fuel (σ_{live} , σ_{woody})	m^{-2}/m^{-3}
δ	Fuel depth	m
M_x	Fuel moisture extinction	-
h	Heat content of the fuel	kJ/kg

Symbol	Parameter/constant	Value(unit)
S_T	Total mineral content	5.55%
S_E	Effective mineral content	1.00%
ρ_P	Oven-dry particle density	32 kg/m^3
σ	σ_{10hr}	3.57 m^{-1}
	σ_{100hr}	0.98 m^{-1}

Table 1. Input variable and parameter into Rothermel's fire model

2.4.4. Rate of spread

First attempts concerning mathematical models, making quantitative estimations of ROS and IR, were performed in the early 70s. Authors have realised that a correct prediction of ROS is given when the fire is being driven by flame radiation, i.e. heat fluxes and required heats of ignition. When fire reaches the called “quasi-steady state” (point 2.2) the ROS is then a ratio between the heat flux received from the fire and the heat needed for a latent fuel to be ignited (Rothermel 1972). Frandsen (1971), applying the conservation of energy principle, has proposed the following theoretical relation:

$$R = \frac{I_{xig} \int_{-\infty}^{0} \left(\frac{\partial Iz}{\partial z}\right)_{z_c} dx}{\rho_{be}\ Q_{ib}} \tag{1}$$

Where:

R = quasi-steady rate of spread.

I_{xig} = horizontal heat flux absorbed by a unit volume of fuel at the time of ignition.

ρ_{be} = effective bulk density (amount of fuel per unit volume of the fuel bed).

Q_{ig} = heat of pre-ignition (the heat required to bring a unit weight of fuel to ignition).

$\left(\frac{\partial Iz}{\partial z}\right)$ = the gradient of the vertical intensity evaluated at a plane

z_c = constant depth of fuel bed.

The horizontal and vertical coordinates are x and z, respectively.

At that time it was not possible to find an analytical solution due to the existence of certain unknown parameters. Rothermel (1972) introduced the experimental and analytical formulation obtained in the laboratory (cited formulation is included in Annexe 7.1). The result given is:

$$R = \frac{(I_p)_0 (1 + \phi_w + \phi_s)}{\rho_b\ \varepsilon\ Q_{ig}} \tag{2}$$

This expression about ROS has two relevant signs of identity. Firstly, since all parameters except mineral content and moisture of extinction are measurable in the field, these equations were and still are currently embedded in many fire behaviour models applied worldwide (Rothermel 1972; Chandler et al. 1983). The other distinguishing features allow the assumption of elliptical spread shape in order to develop an algorithm aiming at fire growth computation. There is a direct dependence between elliptical fire shape and the rate of spread behind Rothermel's formulation and it is because it just takes into account the front part of the fire simulation (Rothermel 1972). Minor formulation adjustments have been done by Albini (1976a) afterwards.

Anderson et al. (1982) describes the elliptic spread's shape mathematically by parametric equation based on different scenarios, firstly with no wind effect and secondly under constant wind (parameterization included at Annexe 7.2 point 1.). The authors come up with a modification of Huygen's principle to model growing fire spread in non-uniform conditions. The principle can be imagined as a fire propagation over a finite time interval using points which define the fire front. At the same time independent ignition sources of small elliptical wavelets can be settled in there. These fires create an envelope around the original perimeter, where the outer edge represents the new fire front (Annexe 7.2 point 2.). This process has been referred to as Huygens' principle (Anderson et al. 1982). This approach allowed computer implementation of forest fire modelling in many models.

Research related to computation of the rate of spread is mainly based on Rothermel's equations. Nevertheless it only takes into account the front part of the fire simulation. Limitation such as spread of fire by firebrand or crown fires were not included subtracting reliability and accuracy to the estimations. Further implementations of surface fire behaviour have introduced sub models in order to implement the overall calculations. The inclusion of crown fire behaviour instead of just superficial spread (Wagner 1977; Rothermel 1991; Scott and Reinhardt 2001; Finney 2004), the creation of new fires generated by spotting effect (Albini 1979) and post-frontal combustion (Finney et al. 2003) allow much more realistic estimations and a better understanding about how fire behaviour performs.

2.4.5. Fire intensity

Reaction intensity of a surface fire refers to thermal energy production (i.e. rate of released energy per unit area) at the flaming front. It was defined by Rothermel (1972) and subsequently re-adapted by Wilson (1980):

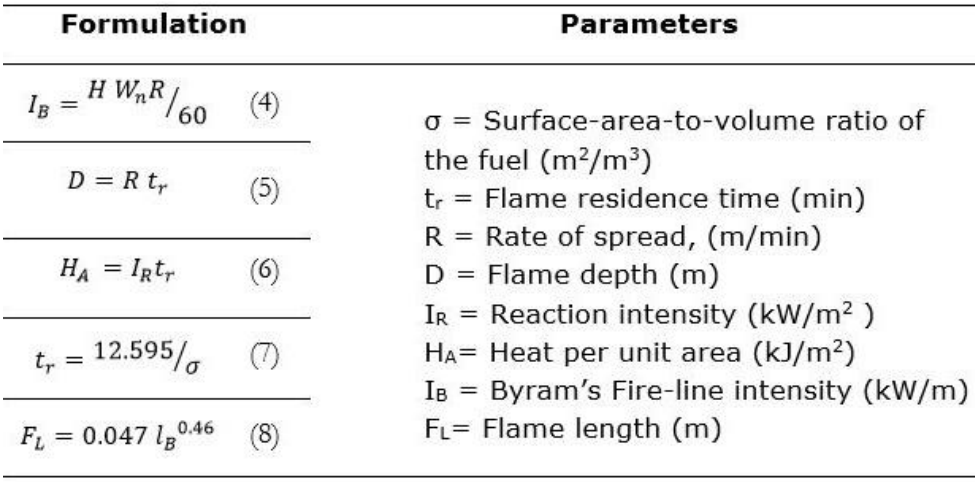
$$I_R = \left(\frac{1}{60}\right) \Gamma' \, w_n \, h \, \eta_M \, \eta_S \tag{3}$$

Where:

IR = Reaction intensity (kW/m^2)
Γ´ = Optimum reaction velocity (min $^{-1}$)
w_n= Net fuel load (fuel after substation of its mineral content (kg/m^2
h = Heat content of the fuel (kJ/Kg)
η_M= Moisture damping coefficient (from 0 to 1)
η_S= Mineral damping coefficient (from 0 to 1)

2.4.6. Byram's fire-line intensity, flame length and heat per area

The mathematical relation among IR, HPA and FML described by Andrews (1986) (conveniently adapted to SI units) together with FLI formulation prescribed by Byram (1959) are summarized in Table 2:



Formulation		Parameters
$I_B = {}^{H\, W_n R}/_{60}$	(4)	σ = Surface-area-to-volume ratio of the fuel (m^2/m^3) t_r = Flame residence time (min) R = Rate of spread, (m/min) D = Flame depth (m) I_R = Reaction intensity (kW/m^2) H_A= Heat per unit area (kJ/m^2) I_B = Byram's Fire-line intensity (kW/m) F_L= Flame length (m)
$D = R\, t_r$	(5)	
$H_A = I_R t_r$	(6)	
$t_r = {}^{12.595}/_{\sigma}$	(7)	
$F_L = 0.047\, l_B^{0.46}$	(8)	

Table 2. Fire Intensity-related equations

Reaction of intensity was taken directly from Rothermel (1972). Heat per unit area is obtained from the multiplication of Rothermel's reaction intensity and Anderson's residence time (Anderson 1969), being the latter a function of the diameter of the fuel, directly related to time lag (point 2.3.2). Fire-line intensity, also called Byram's intensity (Byram 1959) can be derived from three different combinations of Rothermel's model variables. It is considered one of the most useful fire intensity's measures (Chandler et al. 1983). Flame length is directly related to fire-line intensity.

2.5. What should a fire model embedded in a DGVM consider?

Coupling a fire model into a DGVM allows the simulation of inter-related processes between the vegetation dynamics-climate-fire behaviour predictions as well as the understanding of how feedback loops affect the overall balance of the system. This task is challenging since there are many multi-directional processes working at the same time and because they are affected by the performance of several parameters simultaneously. The delineation of clear and precise components of conceptual framework and its boundaries are needed in order to properly address fire modelling within dynamic global vegetation models.

Fosberg et al. (1999) suggested a model framework with climate, fuel's load-size-moisture, plant functional types (PFT) composition and stand structure as input data for the fire module. The fire behaviour unit can be divided into different subsections based on the processes involved, represented at Figure 6.

Weather, fuel, ignition source (natural and human based) and topography parameters influence how fire ignites. On the basis of these, ROS (more or less complex depending if spotting or crowing calculations are included) performs as a consequence of wind, dead-living fuel and the physics behind fire spread computation. Given a specific ignition and spread, but also depending on fuel characteristic, the effects allow quantification of fire intensity, fuel weight loss as well as plant damage and mortality. The two latter directly affect biomass burning emissions. Carbon emission, remaining PFT, stand structure or vegetation dynamics are potential output data prescribed by Fosberg et al. (1999) and plausible research target for feedback loop assessment linking either fire, vegetation and/or climate.

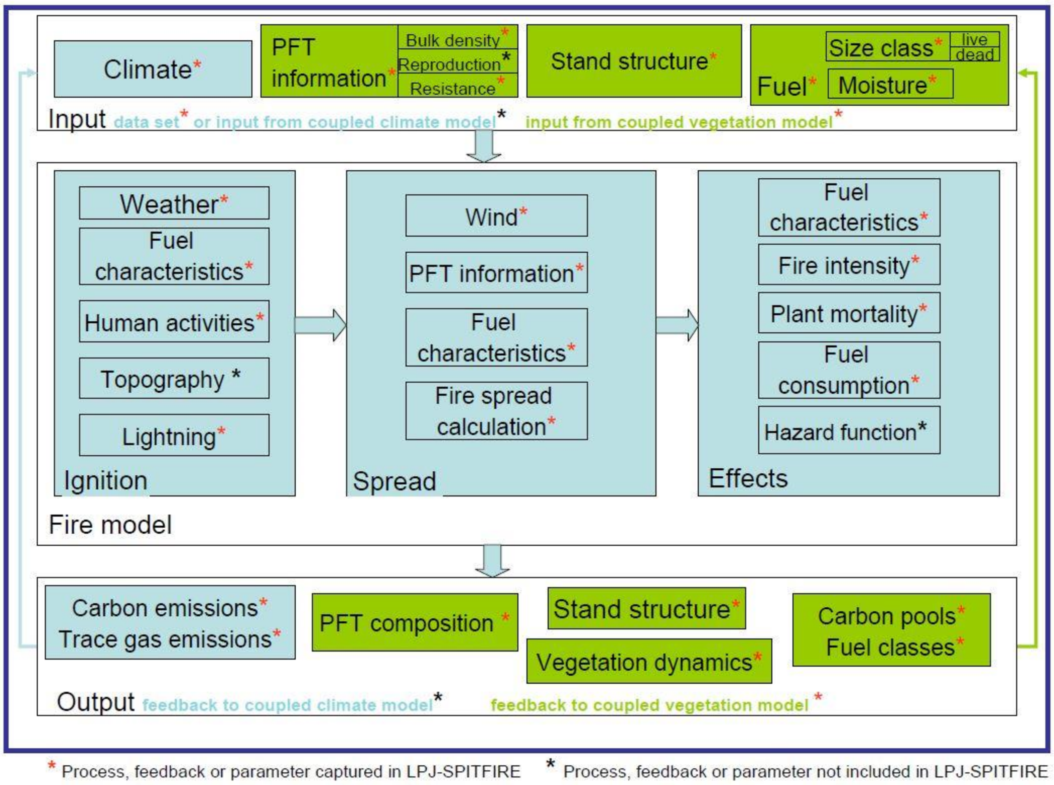


Figure 6. Framework description of the important component a coupling fire model-DVGM should include. By Thonicke et al. (2010) based on Fosberg et al. (1999)

3. Methodology

In order to assess the potential embedment of a dynamic vegetation model (LPJ-GUESS) into a spatial-explicit fire behaviour model (FARSITE), certain questions need to be answered following the methodology presented in this chapter. A brief description of the study area, followed by a sketch of the main model's characteristics is presented here. The method continues by: (1) assessing variable selection at which FARSITE needs to be run, (2) assessing initializers parameters at which LPJ-GUESS-SPITFIRE needs to be run, (3) implementing the source code in LPJ-GUESS-SPITFIRE, (4) simulating the typical LPJ-GUESS conditions within the case study area, (5) running FARSITE for the range of conditions in LPJ-GUESS-SPITFIRE and (6) comparing of the results from LPJ-GUESS-FARSITE with the results from LPJ-GUESS-SPITFIRE.

3.1. Study area

The Provence region is located in the south-eastern part of France (Aix-en-Provence 43°22N 05°27E). France is considered one of the five southern member states in the EU that is most affected by wild-fires (JRC-EFFIS 2012) since 2005's annual report. For instance, in 2012 the annual burned area on average was counted on 8.600 ha whereas 26.383 ha were affected by fires from 1980 to 2001. Fire, a significant disturbance factor in Provence's region, plays an essential role within the vegetation dynamics shaping the structure and composition of the landscape (Pausas 1999; Curt et al. 2011; Schaffhauser et al. 2011).

A widespread range of Mediterranean type fire-prone ecosystems (MTEs) covers this region (Curt et al. 2010). The study area is mostly based on shrublands, forest and grassland. Afforestation of conifer species, abandonment of agricultural land facilitating the shrubland's expansion as well as population's increase constitute the main drivers behind fire risk (Moreira et al. 2011; Curt et al. 2013). In this region two key landscapes, based on soil substrate, were classified by Quézel and Médail (2003). As a result of this categorization, (Curt et al. 2010) described the relation of soils with regards to the presence of dominant vegetation. For instance: (1) limestone substratum is characterized by *Quercus coccifera* (shrub), *Quercus Ilex*, *Quercus pubescens* and *Pinus halapensis* (both forest) (Ganteaume et al.

2011), whereas (2) siliceous/acidic substrata is dominated by *Erica-Cistus spp* (shrub) and *Quercus Suber* (forest)(Curt et al. 2009). A table with further explanation on the main characteristics of the fuel types (Curt et al. 2013) is enclosed in Annexe 7.3.

The siliceous area, belonging to the so-called Maures massif (shown in Figure 7, within the red boundary), is influenced by Mediterranean climate. Following the climatic indices given by Sitch et al. (2003), Maures massif fits in the bioclimatic zone 8. This represents a drought tolerance >0.4, temperature of coldest month >1.5ºC and growing degree days (5ºC)>2500. The mean annual rainfall approaches the 550 mm in lowland but ca. 1000 mm/year on the massif ridges, whilst the mean annual temperatures are 15.9ºC. These conditions, together with high inter-annual and seasonal variability plus strong winds and tendency to droughts, make the Provence region a fire-prone environment (Curt et al. 2013).

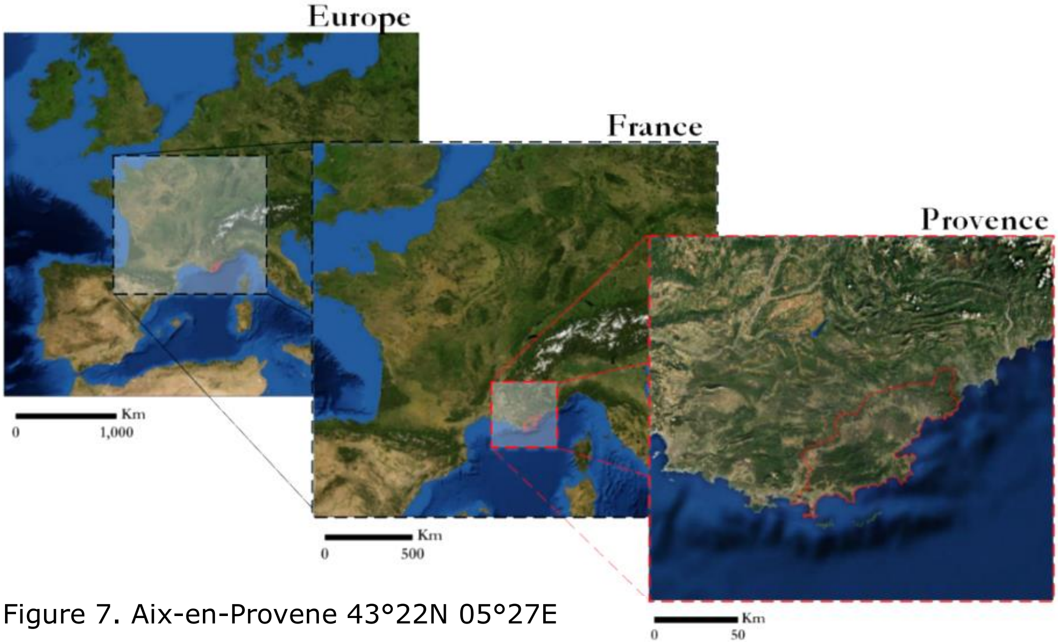


Figure 7. Aix-en-Provene 43°22N 05°27E

3.2. *Fire behaviour models*

3.2.1. LPJ-GUESS-SPITFIRE

The structure, composition and dynamics of terrestrial ecosystems can be modelled with LPJ (Lund-Potsdam-Jena) framework at different scales, ranging from landscape up to worldwide scale. The representation of the vegetation in LPJ is characterized by Plant Functional Types (PFTs). PFT refers to a set of one up to large number of species with similar characteristics such as growth form (grass, shrub or tree), leaf form (broad or needle leaf), leaf phenology (evergreen, summer-green or rain-green), leaf physiology (C_3 or C_4 grasses) and bioclimatic limitations (drought tolerance, temperature of coldest month or growing degree days on based 5ºC)(Fosberg et al. 1999; Smith et al. 2001; Sitch et al. 2003). In LPJ version 2008 there are 20 PFT, 18 woody-based species and 2 types of grasses. An overview of PFT present in the study area as well as its taxa characterization and description is included in the Annexe 7.4.

Fire was the only natural disturbance computed in the very first version of LPJ (Sitch et al. 2003). However, this first formulation was rather simple and further development was required due to the significant limitations concerning fire performance. Advances were achieved by Thonicke et al. (2010) when coupling SPITFIRE (Spread and InTensity of FIRE) to LPJ, making it a complementary module within LPJ-DVGM. The model performs dynamic vegetation in population mode. The population mode means that each PFT is described by a single average individual, representing the average state of all individuals of this PFT over a larger area. Hence fires could not influence the age structure of the vegetation as this is pre-defined.

SPITFIRE characteristics include explicit fire ignition by lightning and/or human-caused. Ignition occurs only if: (1) fuel is present/available, (2) fuel is dry enough and (3) minimum temperature precedes the fuel's ignition. Litter loading is dynamically derived from LPJ, while fuel loading and fuel moisture are calculated within the fire module (characterization of fuel loading is given in point 3.3.1.) The fuel moisture content is derived from Nesterov Index (NI)(Nesterov 1949). NI is related to the fuel dryness in such a way that accumulates days with precipitations ≥ 3mm and above-zero temperatures (i.e. the lower NI, the less dryness). LPJ-DVGM-SPITFIRE follows Rothermel’s fire spread formulation including the elliptical-shape-spread assumption (Rothermel 1972; Pyne et al. 1996). The model allows explicit ROS computations together with fire reaction intensity. The model also calculates crown scorch, following Wagner (1977), as well as post-fire damage. Burning emissions (CO_2, CO, CH_4, VOC, NO_x and total particulate matter) are calculated based on fuel combustion thresholds depending on characteristic PFT’s emission factors.

Although more similar in structure and formulation than in the dynamic vegetation (DVGM) version, LPJ-GUESS (General Ecosystem Simulator) 2nd generation offers an alternative set up of LPJ framework. It performs in cohort mode within a number of replicates/patches in each grid cell (0.1Ha~one large adult individual tree). A cohort stands for a group of PFT with the same age class, i.e. identical establishment times (Smith et al. 2001). Plant establishment, vegetation competition (for nutrients, light or water), successional dynamics, mortality and disturbance are commonly included as stochastic processes providing different dynamics at different patches. In LPJ-GUESS the individuals are representing age cohorts of similar properties. Besides, there is no explicit spatial representation either for PFT or fire behaviour (Smith et al. 2001).

LPJ-GUESS-SPITFIRE (C++ programming language-based) was compiled in C++ using the IDE ECLIPSE, working in LINUX OS in this work. The coordinates introduced inside the gridlist.txt were 5º23’ longitude - 43º2’ latitude, being positioned at Provence region. Observed climate data (Lonstr-1.db) was used for calculations. The cited weather database includes daily data from 1979 to 2009 regarding precipitations (mm), sun radiation, i.e. sward, (W/m2), temperature (ºC), wind speed (m/s), Nesterov Index and relative humidity (%). LPJ-GUESS-SPITFIRE also requires complementary data such as CO_2 concentrations in ppm (Co2_1901_2006.txt) together with soil data (soil.db) in order to carry out the calculations.

3.2.2. FARSITE

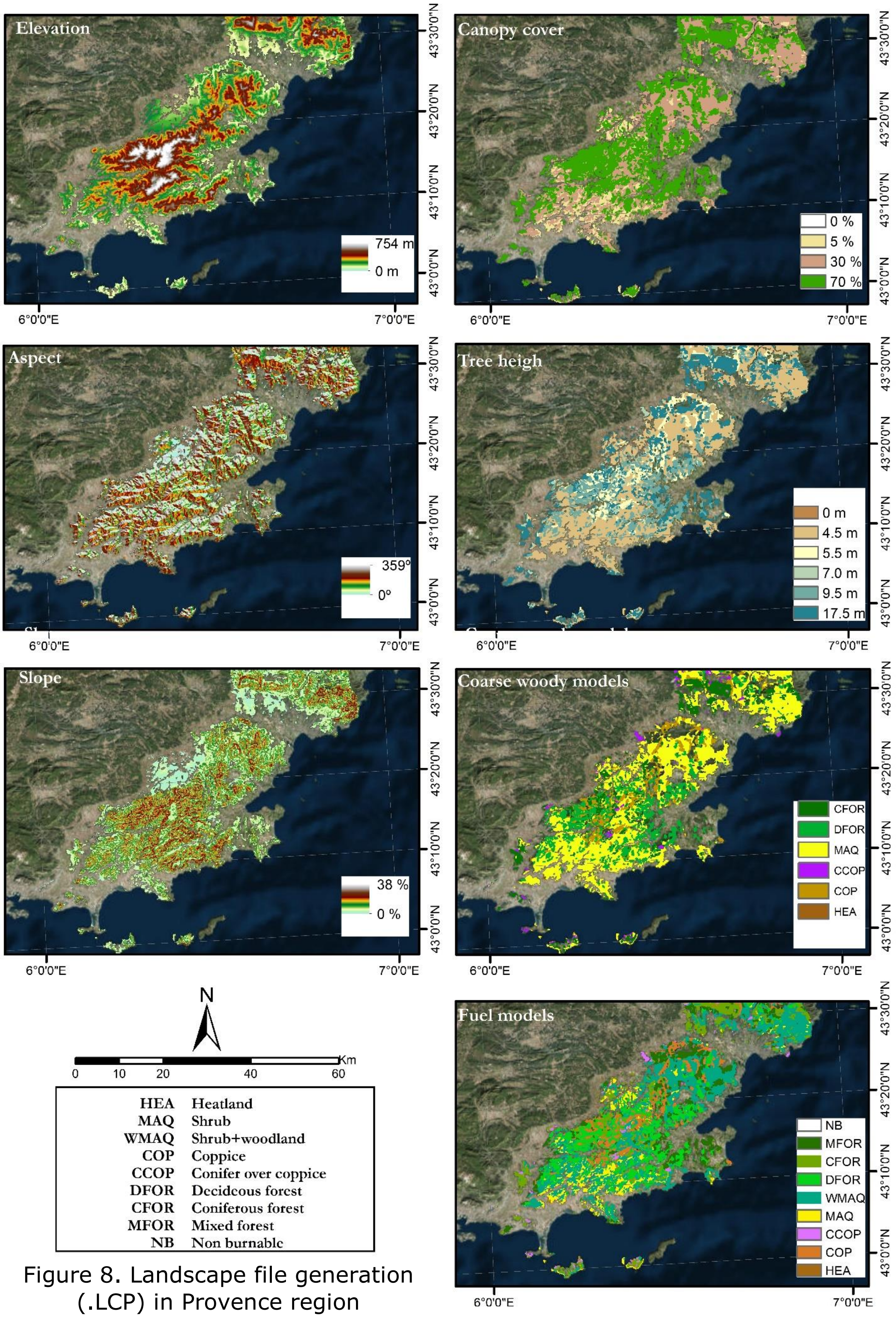
FARSITE (Fire Area Simulator) is a two-dimensional deterministic non-dynamic fire-growth model which allows explicit spatio-temporal representation at landscape scale. The need for a single tool with the purpose of interconnecting fuel’s treatment, effect of weather and topography have motivated the development of FARSITE (Finney 2004). The model takes account of fire behaviour characteristics such as: (1) superficial or transition to crown fire computation following either Finney (2004) or Scott and Reinhardt (2001) method, (2) spotting process allowing ignitions of new fires (Albini 1979), (3) point-source fire acceleration (FCFDG 1992), (4) fuel moisture evolution depending on previous weather conditions and (5) post-frontal combustion, implemented afterwards by Finney et al. (2003) containing the "Burnup" sub-model (Albini and Reinhardt 1995).

FARSITE is based on Rothermel's physical fire spread model (including Albini (1976a)'s implementation). Fire shape is assumed to be ellipsoidal despite the fact that it is only suitable for uniform conditions (like topography, fuel or weather). Huygen's principle (point 2.4.1) is introduced in the model's framework. Accordingly, fire shape and direction are defined by wind and slope whilst size is determined by ROS and burning period (Finney 2004). FARSITE assumes a sequential fire activity conditional upon the environmental conditions, fuel availability and topography. In this sense, fire can start as superficial-based, burning grasses, litter, shrubs or understory woody debris. If conditions favour the combustion, fire accelerates until the steady-state equilibrium is reached (point 2.2). Potential transition to crown fuels is then possible if canopy cover is accessible. Synchronously, the model assumes that spotting processes are allowed only if crown fire occurs.

A FARSITE version 4.1 working on WINDOWS OS was utilized for the purpose of the thesis. The standard data-set required by the model is mostly based in two differentiated input components. First of all the landscape file generation (.LCP) involves a number of raster (.ascii) files which the model overlays. These files must have identical spatial resolution, size and projection. LCP must include elevation, aspect, slope, fuel model and canopy cover themes. Additionally, in order to perform more realistic post-frontal combustion's simulation, the authors recommended complementing them with canopy cover, tree height, crown bulk density, duff loading and coarse woody models. Secondly, FARSITE requires the following (compulsory) data inputs: the preceding landscape file (.LCP), custom fuel characteristics (.FMD), a fuel adjustment (based on expert knowledge) file (.ADJ), fuel moisture (.FMS), coarse woody profiles (.CWD) as well as up to 5 weather (.WTR) and wind files (.WND).

The data-set used in the study (provided by IRSTEA) contains an .LCP file with typical topography, vegetation, and dead and living fuel distribution along Provence's region. A map composite (Figure 8) of all elements are presented. All these data have been collected during several studies from 2006 to 2012, generally from May to October (Ganteaume et al. 2009; Curt et al. 2011; Schaffhauser et al. 2011; Schaffhauser et al. 2012a).The last study was conducted in 2011-2013 by the PhD student Thibaut Fréjaville although the research remains unpublished.. It includes three topographic raster layers together with canopy height (6 classes from 0 m up to 17.5 m), canopy cover (4 classes ranging from 0 to 70%), custom fuel model (9 classes including 1 non-burnable) and the coarse woody model (6 classes) data. The custom fuel model (.FMD) includes vegetation type, fuel's code, fuel model name, characteristic dead fuel's load, fuel depth, initial dead/ live fuel moisture and moisture of extinction. Original data is derived from ca. 20-30 field surveys for each fuel model. Because of the confidence intervals are rather slow, the values of fuel load and fuel depth are mean values. Dead and living fuel moisture percentages have been standardized to the fuel moisture scenarios proposed by FARSITE.

FARSITE exports both vector files (ArcView shapefile format) and raster (GRID ASCII format) files. Likewise explicit front-fire behaviour computation such as rate of spread (m/min), reaction intensity (kW/m^2), fire-line intensity (kW/m), flame length (m) and heat per area (kJ/m^2) have been exported.



HEA	Heatland
MAQ	Shrub
WMAQ	Shrub+woodland
COP	Coppice
CCOP	Conifer over coppice
DFOR	Decidcous forest
CFOR	Coniferous forest
MFOR	Mixed forest
NB	Non burnable

Figure 8. Landscape file generation (.LCP) in Provence region

3.2.3. LPJ-GUESS-FARSITE

The following process-based meta-model sketch illustrates the ingredients for a unique and novel approach, which should contribute to a better understanding of the relationship between fire regimes within the climate system and its influence on the vegetation-dynamics (see Figure 9). Note that the fire behaviour calculated in FARSITE impacting the vegetation in LPJ-GUESS-SPITFIRE was not achieved in this thesis.

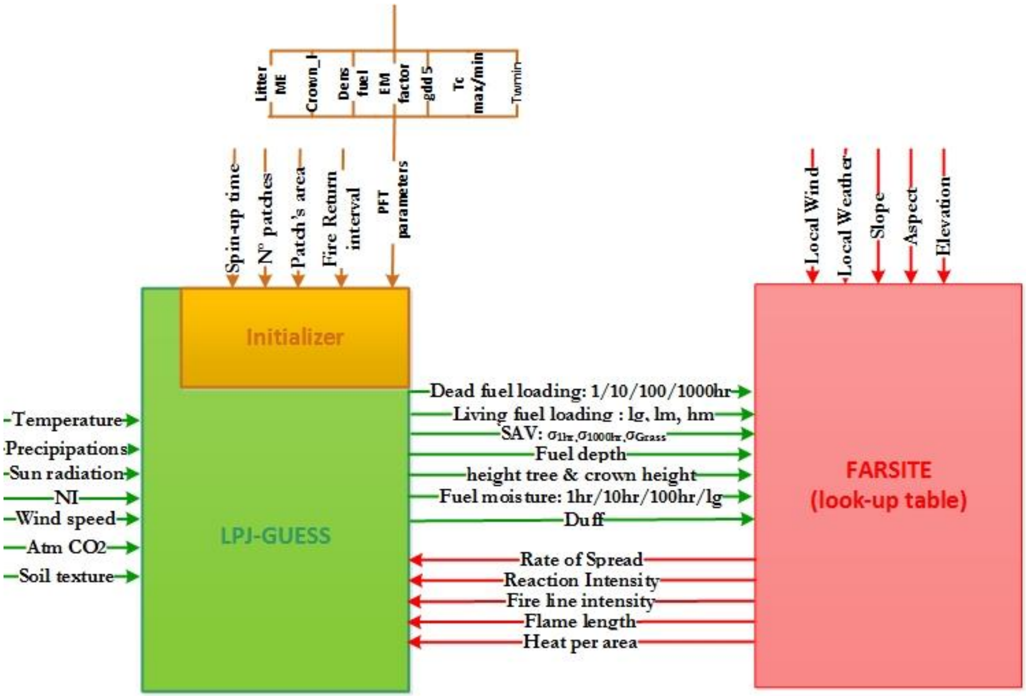


Figure 9. Conceptual diagram LPJ-GUESS-FARSITE

3.3. Model's set up

3.3.1. Assessing the variable and parameters selection from LPJ-GUESS-SPITFIRE

As a starting point the output data selection was carried out by using LPJ-GUESS-SPITFIRE model (Thonicke et al. 2010) in order to evaluate how many parameters can be used as data input for the explicit fire behaviour FARSITE model (Finney 2004). Target parameters for the study are mostly based on the vegetation-related modules.

Firstly, the technique was based on the analysis of input data required by FARSITE: what data are either compulsory or optional, metric units required, file format as well as the file extension needed (table enclosed at Annexe 7.5). Secondly, there was an assessment of the logic behind the model's code for each state variable (structures such as litter, fuel loading or canopy cover) and process of interest (functions such as increase of biomass or fuel moisture variations). The goal was to evaluate the adaptable variables and parameters into FARSITE.

LPJ-GUESS framework includes different modules interrelated representing performance of plant phenology and growth, population dynamics, migration, soil organic matter dynamics (SOM) (Smith et al. 2001) and fire dynamics, model developed by Thonicke et al. (2010). Fire.cpp, growth.cpp, guess.cpp, somdynam.cpp, vegdynam.cpp codes plus the initializer guess.ins.txt were studied to be able to search for suitable variables, related constants and units utilized. In order to keep the parameter selection as clear as possible, a sub-classification by theme was carried out (table-summary included in Annexe 7.6):

3.3.1.1. Fuel loading, SAV, Mx and fuel depth

The aboveground litter pool of each patch is divided into a number of state variables according to tissue (leaf and wood) and PFTs. In LPJ-GUESS-SPITFIRE, the living biomass becomes dead fuel when either turnover or mortality transforms it into litter. Different fuel's diameters (based on time lag concept, point 2.3.2) are defined by multiplying allometric relations. The product separates leaf from woody litter: fuel_1hr_total (leaves and twigs), fuel_10hr_total (small branches), fuel_100hr_total (large branches) and fuel_1000hr_total (boles or trunks). The application of a conversion factor from dry-mass to carbon in the first three fuel classes resulted in dead fuel loading (gDM C/m^2). Uniquely 1hr,10hr and 100hr fuel loading are taken into account since only they influence ROS (Rothermel 1972; Pyne et al. 1996). Additionally, live grass fuel loading (LiveH) was calculated in dry-mass basis (gDM/m^2) taking into account the grass phenology simulated in vegdynam.cpp. The thickest fuel class (representing trunks and boles, fuel_1000hr_total) characterized the live woody (LiveW) loading (gC/m^2). However, due to the fact that LPJ only burns dead fuel and ignores living non-leaf fuel, identical values provided by IRSTEA have been used.

The Surface-to-volume (SAV) ratios are constant values (cm^2/cm^3) for each fuel class. Different SAV are represented by sigma_1hr, sigma_10hr, sigma_100hr, sigma_1000hr and sigma_grass. The fact that SPITFIRE used fixed values for all types of fuel is cumbersome since each custom fuel model in FARSITE requires a specific SAV ratio for fuel 1h, LiveH, LiveW; whereas fuel 10h and fuel 100h remain constant (reviewed in point 2.4.3). In this sense, both models fully agree with respects to the latter assumption.

Litter flammability moisture factor (so-called litterme) is prescribed as a constant parameter for trees, shrubs and grasses (i.e. PFT specific). Litterme establishes the benchmark at which the fire does not spread. The specific value of moisture of extinction (Mx) is represented by the variable char_moistfactor. It changes over time depending on fuel moisture and NI. FARSITE requires an explicit moisture of extinction value for each custom fuel model.

Heat content (kJ/kg) is constant for both living and dead fuels. Despite the fact that FARSITE requires a specific heat content value for each custom fuel model, the variability is fairly small, therefore LPJ has generalized it to 18000KJ/Kg. Even though fuel depth (cm) is not explicitly computed by LPJ-GUESS-SPITFIRE, it can be easily calculated by dividing total oven-dry fuel load (dead_fuel, gDM/m^2) by oven-dry particle density (char_dens_fuel_ave, in kg/m^3).

3.3.1.2. Fuel moisture

Fuel moisture in LPJ-GUESS-SPITFIRE is estimated based on Nesterov Index (Lehsten et al. 2010; Thonicke et al. 2010). A litter moisture index weighed per each dead fuel class is computed (dlm and dlm_grass). No fuel moisture output from living wood is performed.

3.3.1.3. Stand tree parameters

Parameters related to standing trees have a direct influence over the crown fire performance. Stand tree height can be directly interpreted from LPJ-GUESS. It is the height from the soil to the top of the canopy. On the other hand, crown base height did not have a straight translation in the framework. However, its calculation simply required a multiplication of the proportional crown's length to the total tree height (both measured in m). Crown bulk density (kg/m^3), which gives a volumetric measurement of the tree canopy weight, is not explicitly calculated by LPJ. Finally, tree canopy cover (%) is defined by foliar projective cover (fpc_tree) under full leaf cover as a fraction of the modelled area. Grass cover is also calculated following the same procedure.

3.3.2. Assessing initializers parameters at which LPJ-GUESS-SPITFIRE needs to be run

Since FARSITE performs explicit behaviour of fire events, it requires the conditions before ignition. For this reason the goal is to get outputs from LPJ as close as possible to FARSITE's inputs dataset. Five important parameters in LPJ's set-up needed careful consideration: (1) temporal frame, (2) number of patches (npatch), (3) fire return interval (fixreturnfireinterval), (4) the PFT which are present/absent and (5) burning day (fixburnday).

3.3.2.1. Temporal frame

A model initializer document (guess_ins.txt) was set-up in such a way that during 1000 years LPJ performed a spin-up period. In this period of time, vegetation composition and its structure as well as soil and litter carbon pools reached an equilibrium. An equilibrium that included vegetation's dynamics, the ecological succession of the PFT and the impacts due to disturbances. The spin-up period is followed by 30 years of the so-called historical phase. Historical data established the temporal frame in which post-analysis of LPJ outputs have been conducted.

3.3.2.2. Number of patches

An evaluation of the required number of patches was performed in order to get a compromise overview of between computational effort and model stability. The more patches, the higher the amount of replicates, the lower is the variability of the mean value. For my work, a number of 100 patches seemed to be ideal, since the results were stable and the time for calculation was suitable.

3.3.2.3. Fire return interval

The fire return interval parameter defines the period of time between fire events. This parameter was included in SPITFIRE for testing purposes. The model also allows stochastic fire occurrence (fixrandfirereturninterval) even though this option was neglected since there is no control over the process itself. Fire return interval directly affects the vegetation dynamics such as succession stage, PFT presence before/after fire as well as the performance of variables such as living and dead fuel loading, stand height, crown base height or canopy cover. Depending on how these parameter is set up, a completely different vegetation composition is modelled. According to Curt et al. (2013) the study area shows a fire return interval of 22 years for shrubs, 24 years for pine forest and 27 years for oak forest. The areas burned from 1 up to 2 times from 1960 to 2010. This benchmark suggested a suitable time-frame of 25 years fixed-return-fire-interval.

3.3.2.4. PFT

LPJ-GUESS-SPITFIRE version 2008 computes 20 different PFTs. Since the study area focusses on Mediterranean conditions, calculating all of them would increase simulation time and storage efforts for the results unnecessarily. Once the coordinates have been adjusted, preliminary runs in LPJ were simulated (from 1 to 100 patches along 10, 20, 30, 40, 50 and 60 return fire intervals) in order to assess the typical PFT environment at Provence region. None of the boreal PFT like pLSE, BES, Bet_pub, Pic_abi or Pin_syl were present. Also temperate types such as Bet_pen, Car_bet Pop_tree, Abi_alb and tropical C4 grasses were disabled from the initialization's file.

3.3.2.5. Fixburnday

For simplification purpose, 1st of August (day 213 of the year) was selected as fixed burning day. Disregarding stochastic fire ignition during any other time periods, the model allowed to keep more control over the vegetation’s succession. It was also noticed from literature that the greatest percentage of fire disturbance in Provence occurs during the summer periods (Schaffhauser et al. 2011; Curt et al. 2013). LPJ-GUESS-SPITFIRE burned the 100 patches selected.

3.3.3. Code’s implementation in LPJ-GUESS-SPITFIRE

In order to perform the analysis planned, alterations on the model’s code were indispensable. With the original structure of the model, an evaluation in such detail as the one attempted would not be possible. For this reason, an implementation of the code was carried out:

1. Identification of year of occurrence during the simulation run. This could be done including the printf functionality within guess.cpp module. It helped in the understanding of the time-frame during modelling (Annexe 7.7, point 1).
2. Implementation of eight new variables (crown base height, fuel depth and fuel moisture 1h, 10h, 100h, flame_length, flame_residence and heat_per_area) which can be calculated directly from SPITFIRE's code. The first five variables are required as input by FARSITE. Crown base height is calculated from the multiplication of tree height and crown length proportion. Fuel depth derives from dead load fuel (1h+10h+100h) divided by the fuel's density (Pyne et al. 1996). Following the same structure used by Thonicke et al. (2010) for fuel moisture calculation (composite estimation of moisture content for 1h, 10h, 100h fuels), a decision of splitting up the calculation for each specific fuel class was taken (Annexe 7.7, point 2). On the other hand, the incorporation of these three fire behaviour new variables allowed the comparison of outcomes between models. Both equations are prescribed from Andrews (1986).
3. The addition of printf (“on-the-fly”) commands for each of the target’s variables, both included in fire.cpp and growth.cpp. Printf statements allowed variable’s identification and anomalies’ check together with the understanding of their performance from one year to the next (Annexe 7.7, point 3).

4. After having analysed some of the output generated, it could be observed that the spin-up time (1000y) plus historical phase (30y) did not match with time sequence from the variable's calculation (point 3). It was noticed that fuel-related characteristics were calculated only if a fire event occurred. This fact is directly related to fixfirereturninterval parameter. In order to keep track of the overall behaviour of such variables, it was vital to induce fire.cpp module run during non-fire years as well. For this purpose, the loop which involved whole computation of fire parameters and processes has been moved down in the code, allowing fire-related calculations even if there is no fire phenomena. The reason behind it is in the interest of keeping daily/yearly track of dead and living fuel loading, fuel moisture, fuel depth, moisture of extinction and tree-related characteristics (Annexe 7.7, point 4).

5. LPJ-GUESS-SPITFIRE does calculate all variables as a whole, summarizing all PFT per patch at the same time. To deal with the original configuration was challenging because it did not specify what is what or where the estimations came from. The analysis could derive into misinterpretation from the outcomes generated. For this reason, the variable’s selection was separated by “PFT-specific”. This means that instead of managing average values, each of the variables are calculated based on specific PFTs/species. The methodology required a declaration for all variables based on array lists with 20 spaces (20 for each possible PFT).

   In order not to interfere in the regular set-up of calculations from LPJ-GUESS-SPITFIRE, all functions, loops and variable’s interrelation along the code were mimicked. For instance, a dual version from the same routine has been performed: no PFT- and PFT-specific. Before carrying out any analysis of the results, a test was done to see if the outputs with all PFT actually calculated the same values as PFT specific. As a result, it was verified that dead fuel 1h,10h, 100 h, live grass fuel loading, and fuel depth were calculated summarizing all PFT. (See Annexe 7.14).

6. Similar to the stated in point 5, the addition of a fire behaviour routine “PFT specific” was developed in order to assess how individual species burn on the same patch. For instance, the implementation allows subsequent comparison of SPITFIRE, FARSITE and LPJ-SPITFIRE simulations per vegetation type. A clear relationship between PFT affected by fire and its ROS, FLI, IR, HPA and FLM associated is more enlightening than a mixture of averaged outputs.

7. Next step was based on automatic generation of outputs into .txt format using fprintf functions (instead of printed "on the fly"). This procedure allowed posterior data analysis in Excel and R. Three different themes were developed (Annexe 7.7, point 6):

    - First of all the fuel-related variables in fire.cpp. Each line contains patch ID, year, day, foliar projective cover (tree and grass), dead fuel loading (1hr, 10hr, 100hr and 1000hr), live-grass fuel loading, fuel depth, moisture of extinction, Nesterov Index and fuel moisture (1hr, 10hr, 100hr and grass). Some constraints in the output design were included, such as the writing of only last 30 years (historical phase) as well as only the day before, during and day after fire event.
    - Secondly, the fire behaviour variables, also taken from fire.cpp module. For instance propagating flux, reaction intensity, influence of wind speed, fuel bulk density, packing ratio, heat of pre-ignition, forward and backward ROS, fire duration, forward and backward distance, number of fire, fire danger index, Byram's fire-line intensity, area, flame length and heat per area were exported.
    - Finally, since the information regarding standing tree cannot be calculated on individual basis from the fire.cpp module, a third implementation regarding tree allometry within growth.cpp module was included. Subsequently, yearly records from number of patches, individual height, crown length proportion, leaf, sapwood and heart mass plus DBH were performed.

The cited outputs were created both for PFT non-specific/specific. Unit conversion was indispensable for almost all variables in both codes since FARSITE utilises different units of measurement to those from SPITFIRE. The unit transformations were applied only within the fprintf function instead of inside each routine.

3.3.4. Code's modification in LPJ-GUESS-SPITFIRE.

A detailed analysis over the fire.cpp code has revealed differences in heat of pre-ignition and packing ratio formulas with regards to the presentation of the model in Thonicke et al. (2010). At least two discrepancies with reference to the parameterization proposed by Rothermel (1972) and revised in Albini (1976a) have been detected (Annexe 7.8, point 1). Changes in heat of pre-ignition (Q_ig) together with beta-optimum (beta_opt) parameterization were introduced following Pyne et al. (1996). Reformulation of fire spread equation in Metric Units was prescribed by Wilson (1980). These two parameters have a direct effect over ROS and IR. ROS at the same time influences the so called Bryan's fire-line intensity (FLI) and therefore FML as well. It was hypothesized a decrease in ROS's simulations. Q_ig is dividing ROS, hence an increment in Q_ig will lead to decrease in ROS, thus decrease in FML and FLI as well.

On the other hand, the formula of the area calculated in fire.cpp showed discrepancies between pixel degree size introduced and the area calculation found. At least one order of magnitude seemed to be overestimated (Annexe 7.8, point 2). In theory 1º grid cell along the Equator, where the latitude is 0, should perform an area of 1 e^{10} km^2. But 1.23 e^9 km^2 was calculated instead. The cited pixel degree parameter expects an area of approximately 4 km^2 (this value should be reduced due to the latitude by Earth deformation). However, preliminary calculations of 35.98 km^2 were obtained instead. This area is key variable for the simulation of burning emission.

3.3.5. Assessing parameters at which FARSITE needs to be run

The dataset from Provence provided by IRSTEA has many different vegetation and fuel types. Therefore a very specific target area of study was selected as ignition point. The goal was to mimic the conditions estimated by LPJ-GUESS as much as possible. Mainly shrublands (Quer_coc) and grasslands (C3_grass) as well as lower amount of forest (Quer_Ile, Quer_pub, Quer_pub and Fag_syl) have been simulated in LPJ-GUESS over Provence. For this reason the target area in FARSITE was only based primarily on MAQ together with WMAQ and DFOR fuel models. Fire under COP and CCOP presence have been neglected since man-made management activities can induce to bias.

Since one of the aims is to achieve meaningful and realistic comparison between model's calculations, the conditions in both programs should be as simple and similar as possible. Since LPJ-GUESS-SPITFIRE does not take into account topography, elevation, slope and aspect in its estimations, FARSITE's data set has been transformed to a completely flat surface. For this purpose, the landscape calculator tool included in FARSITE v4.1 was utilized.

3.3.5.1. Set parameters

The grid cell resolution was based on 100m (1 cell=0.1 km^2). Time step computed fire behaviour performance each 30 minutes. The perimeter resolution was set to 60 m and the distance resolution to 30 m. FARSITE's technical reference from User guide always recommends values lower than grid cell resolution. Fire barriers such roads or rivers were not taken into account. Nevertheless, the data-set already neglected land uses such as build-up areas and water bodies. The simulation was set only to one day of duration on 1st of August, mimicking LPJ-GUESS-SPITFIRE set up.

The ignition point was set into MAQ fuel model. The coordinates assigned to the raster cell were 2º33' longitude- 45º89' latitude (Projected Coordinate System: NTF Lambert II étendu; Projection: Lambert Conformal Conic). Crown fire computation was enable following Finney, 1998 method instead of Scott and Reinhardt (2001) method.

3.3.5.2. Input data

For the comparison LPJ-GUESS-SPITFIRE vs FARSITE, the Landscape (LCP) file generation comprised:

- Fuel: (21) HEA, (32) MAQ, (33) WMAQ, (24) COP, (26) CCOP, (37) DFOR, (38) CFOR, (39) MFOR and (99) Non burnable.
- Coarse woody: (21) HEA, (32) MAQ, (24) COP, (26) CCOP, (37) DFOR and (38) CFOR.
- Canopy cover: 0, 5, 30 and 70 %. Stand height: 0, 4.5, 5.5, 7.0, 9.5 and 17.5 m. Crown base height: 1.5 m (constant). Further descriptions in (Curt et al. 2011; Schaffhauser et al. 2011)
- Elevation, slope and aspect set to zero. Similarly occurs with crown bulk density and duff loading.

FARSITE project file have included:

- Landscape file (LCP).
- Fuel adjustments set to 1 (i.e. no change over regular fuel models).
- Fuel moistures 1h, 10 h, 100h, LH and LW. These are the standardized fuel moisture scenarios proposed by FARSITE in summer since almost all fires in Provence are in summer (Curt, T., personal communication, 2014). The values are consistent in

comparison with field measurements calculated by Curt et al. (2011) and also with fuel moisture models described in Salis (2007).

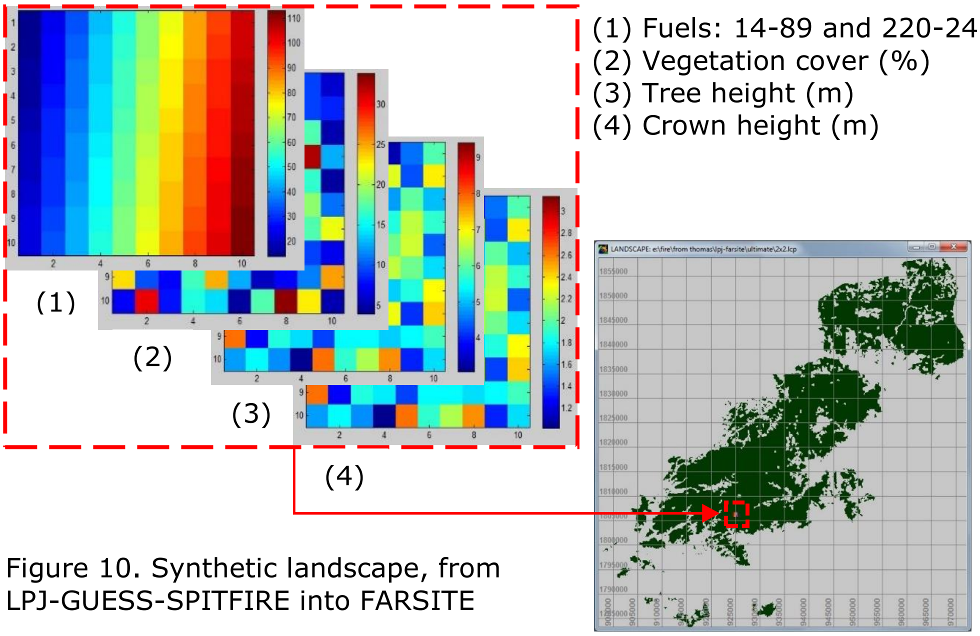
- Custom fuel model 21, 32, 33, 24, 26, 37, 38, 39 and 99 (Code, fuel loading, SAV, fuel depth, Mx and heat content. Data collected from different field campaigns, further description (Ganteaume et al. 2009; Curt et al. 2011; Curt et al. 2013)
- Coarse woody model 21, 32, 24, 26, 37 and 38 (Diameter, fuel loading, heat content, sapwood and heartwood density and moisture). The coarse woody debris were measured in the field between spring and summer of 2012 and 2013 (PhD student Thibaut Fréjaville, remains unpublished).
- Adaptation of SQL weather and wind data. Instead of using only data provided by weather stations close to the study area, a combination of SQL global data (utilized by LPJ) and Hyeres' weather station has been carried out. The reason behind it, is to use as close weather and wind data as LPJ. Hence temperature, precipitations and wind speed are exactly the same. However, some assumptions were mandatory, since FARSITE needs higher detailed weather data in comparison to LPJ-GUESS-SPITFITE. Therefore minimum temperature and maximum temperature were assumed to be 0600 hr and 1500 hr respectively, maximum and minimum humidity were "standardized" from relative humidity. Elevation was set to 85 m above the sea level. Wind direction 135º and cloud cover 0 %.

3.4. Introducing LPJ-GUESS outputs as inputs in FARSITE: LPJ-GUESS-FARSITE's germ

LPJ-GUESS-FARSITE implies the embedment of vegetation related outcomes from LPJ-GUESS within FARSITE fire behaviour model. In order to assess the performance of LPJ-GUESS-FARSITE, the next logical step was to compare the outcomes in fire behaviour from the three models: LPJ-GUESS-SPITFIRE, FARSITE and LPJ-GUESS-FARSITE. The comparison lies within all vegetation types (i.e. non PFT-specific) computed in LPJ-framework. Since there is not a direct connexion between all LPJ-GUESS outputs and FARSITE inputs, several assumptions have been taken into account.

The selection of 100 patches/replicates simulated in LPJ under the effect of 25 years fire return interval was utilized for the design of a synthetic landscape in Provence region. Synthetic landscape refers to an artificial scenario including explicit spatial component, specially designed for the vegetation, calculated within LPJ framework. The specific landscape reproduces identical topographic and weather conditions as those utilized in previous simulations. For this experiment an specific year (i.e. 2004) and specific day (31th of July, one day before the fire event) was set allowing the direct comparison with the burning period performed by LPJ-GUESS-SPITFIRE.

FARSITE requires .ASCII as raster format. Therefore, a code created in MATLAB ® (see Annexe 7.9) was used to convert series of raw data (distributed in columns) generated by LPJ-GUESS-SPITFIRE into a grid-cell of 10*10. For the artificial landscape is assumed that each grid cell in FARSITE has the same area than 1 patch in LPJ-GUESS. The result is a synthetic cubic landscape of 1 km^2 (see Figure 10).



(1) Fuels: 14-89 and 220-243
(2) Vegetation cover (%)
(3) Tree height (m)
(4) Crown height (m)

Figure 10. Synthetic landscape, from LPJ-GUESS-SPITFIRE into FARSITE

Four different raster layers were created based on fuel model, vegetation cover (foliar tree and grass cover), stand height and crown base height, all produced from a series of 100 patches/replicates. In the case of canopy cover, stand height and crown base height simulated values, the procedure is more straightforward. On the other hand, when dealing with fuel classes, additional management is required. Each fuel class associated to each pixel/cell required a link to a specific custom fuel model. Specifically one custom fuel model per fuel class. Each custom fuel model has different fuel loading, fuel depth, Mx and fuel moisture. According to Scott and Burgan (2005), the user is allowed to use any number between 1-256. The latter means that the model allow up to 256 different combinations of typical fuel related variables. However, there is the exception of those already committed to the original Anderson's fuel models; numbers 1-13 (Anderson 1982), and those identified with the Scott and Burgan new fuel models. For example, 91-93, and 98-99 are identified as non-burnable. Therefore, all in all, the approach followed included fuels from fuel model 14 to 89 and from 220 to 243. The cited four raster layers (10*10) are subsequently inserted in FARSITE model (see Figure 10).

The Landscape (LCP) file generation comprised:

- Fuel: 100 fuel models representing each patch/replicate.
- Canopy cover, stand height and crown base height were introduced in each raster cell. In this experiment, mean values were not taken into account.
- Elevation, slope and aspect set to zero. A similar situation occurs with crown bulk density and duff loading.

FARSITE project (FPJ) included:

- Landscape file (LCP) created above.
- Fuel adjustments set to 1 (i.e. no change over regular fuel models).
- Fuel moistures for each patch (1h, 10 h, 100h, LH and LW) taken from each patch. LPJ-GUESS-SPITFIRE does not calculate LW, hence the same value from IRSTEA dataset was kept. On the other hand, all fuel moisture lower than 2% had to be standardized to 2% since this is the minimum value accepted by FARSITE.
- Custom fuel model for each patch (Code, fuel loading, SAV, fuel depth, Mx and heat content). SAV 10-h and 100-h, similarly to LW, were also preserved from fuel models provided by IRSTEA.
- Coarse woody model were disregarded. Due to the species' mixture in each patch, to specify a particular coarse woody model for each patch was not possible.
- Adaptation of SQL weather and wind data, followed the same procedure as explained in 3.3.5.

For this simulation, set parameters such as grid cell resolution, simulation duration as well as ignition point preserved the experimental design presented in point 3.3.5.1.

3.5. Model’s comparison: data analysis

The procedure for data comparison was different depending on the theme assessed. For instance, fuel and tree related variables followed different management to fire behaviour related outputs. On the one hand, PFT specific fuel variables resulting from LPJ-GUESS-SPITFIRE were compared against the fuel model developed for FARSITE, which are based on collected data during several studies from 2006 to 2012. Moreover, fire behaviour outcomes were compared from three different perspectives: (1) comparison of LPJ-GUESS-SPITFIRE before and after having applied the code’s changes, (2) comparison of LPJ-GUESS and FARSITE outcomes and (3) comparison between LPJ-GUESS-SPITFIRE, FARSITE and LPJ-GUESS-FARSITE simulations. In order to do so, histogram and boxplot were created; likewise statistical Shapiro-Wilks and non-parametric Wilcoxon Mann-Whitney analysis were tested.

3.5.1.1. Data preparation

The raw outputs fuel- and tree-related generated by LPJ-GUESS-SPITFIRE in .txt have been pre-arranged following the pivot-table structure (produced in EXCEL 2013®).

The LPJ-based fuel models (Figure 6) included:

- Number of patches (100), mean values of years (30) and day (31st of July) attached as filters.
- PFT: C3_grass, Cor_ave, Fag_syl, Fra_exc, Jun_oxy, MRS, Pin_hal, Que_coc, Que_ilex, Que_pub, Que_rob and Til_cor
- Variables: canopy cover, fuel loading (1hr, 10hr, 100hr and live grass), fuel depth, moisture of extinction and fuel moisture (1hr, 10hr, 100hr and live grass) respectively.

Besides, tree related variables (figure 7) set up has been followed by:

- Number of patches (100), number of years (30) and day (31st of July).
- PFT: C3_grass, Cor_ave, Fag_syl, Fra_exc, Jun_oxy, MRS, Pin_hal, Que_coc, Que_ilex, Que_pub, Que_rob and Til_cor
- Variables: tree height, crown length, dbh, sapwood mass and heartwood mass respectively.

Each PFT has been individually assessed. The approach allowed characterization of fuel- and tree-related variables in pre-fire conditions along 30 years' time-series. Mean values and standard deviation were calculated from all the patches. The presentation of the data follows the same structure as custom fuel model provided by IRSTEA (Table 5). The current format guarantees a direct and interchangeable way of connecting fuel outputs (LPJ-framework) to fuel models (FARSITE). This comparison demanded mean values, even though the current set up allows one fuel model per PFT per day of the year over 30 years' time.

3.5.1.2. Statistical analysis

A statistical analysis was carried out using R software package (R Development Core Team, 2005). All data was separated into independent datasets derived from LP-GUESS-SPITFIRE, FARSITE and LPJ-GUESS-FARSITE models respectively. ROS, IR, FLI, FML and HPA were tested. A normality analysis was performed following Shapiro-Wilks Test. Due to the related samples ranked (i.e. ordinal data that can be put in order) and the fact that the sample distribution does not follow a normal distribution, a non-parametric Wilcoxon Mann-Whitney Test was utilized (Quinn and Keough 2002). Pair-related thematic variables from both models were analysed consecutively. The null hypothesis stated that both populations have identical distribution functions and mean, and it is ultimately identified by the U-test significance.

3.5.1.3. Histogram and boxplot comparison

The data pre-processed obtained from LPJ-GUESS-SPITFIRE and FARSITE has been plotted using R software (R Development Core Team, 2005) together with ggplot2 package. Regarding the script code written in R (Annexe 7.14), data could be entered, plotted and statistically tested afterwards. ROS, IR, FLI, FML and HPA simulated from both models have been assessed. The First experiment compared the performance of LPJ-GUESS-SPITFIRE before and after the code's change. For the second experiment, FARSITE and LPJ-GUESS-SPITFIRE were compared. Finally, a third set of comparisons analysed all three models against each other.

In order to do so, a set of five histograms per experiment together with comparative boxplots (including Min, 1st Quartile, Media, Mean, 3rd Quartile, Max and outliers) was created. Analysing the appearance of each data-set allowed the analysis of the shape, variability and centre of the data. Outcomes from FARSITE, LPJ-

GUESS-SPITFIRE and LPJ-GUESS-FARSITE were combined in the same data-frame even though the sample size was different in each case.

4. Results

The results derived from the assessment presented in the methodology section are disclosed in the following unit. Results are structured in two different themes. The first theme deals with the model's set up, exemplifying the impact of fire return interval over the composition of the vegetation. The influence over the LPJ-GUESS-SPITFIRE code's modification is also presented. The second theme shows, in first place, the comparison of fuel- and tree- related variables calculated from LPJ-framework against the field data provided by IRSTEA; secondly, the fire behaviour results obtained both from FARSITE vs LPJ-GUESS-SPITFIRE and FARSITE vs LPJ-GUESS-SPITFIRE vs LPJ-GUESS-FARSITE.

4.1. Models' set up

4.1.1. Assessing initial parameters at which LPJ needs to be run

The estimations from LPJ-GUESS show a strong (cause-effect) dependence between PFT presence and the fix fire return interval, i.e. fire regime. A comparative Leaf Index Area (LAI= leaf area / ground area, m2 / m2), Biomass (CMASS, kgC/m^2) and Net Primary Production (NPP, kgC/m^2 year) are shown per fix fire return interval in Figure 11 and 12. The stacked-area-plots show the vegetation dynamics whilst there is an increase of 10 years interval between fire recurrences, ranging from 10 up to 60 years return interval. The simulations displayed are based on 100 patches/replicates along 30 years of historical data. Spin up time was neglected. Furthermore Carbon Fluxes emitted by fires (CFLUX, g emission / kg biomass burned) are enclosed as a supplement, linking up fire occurrence and PFT fluctuations.

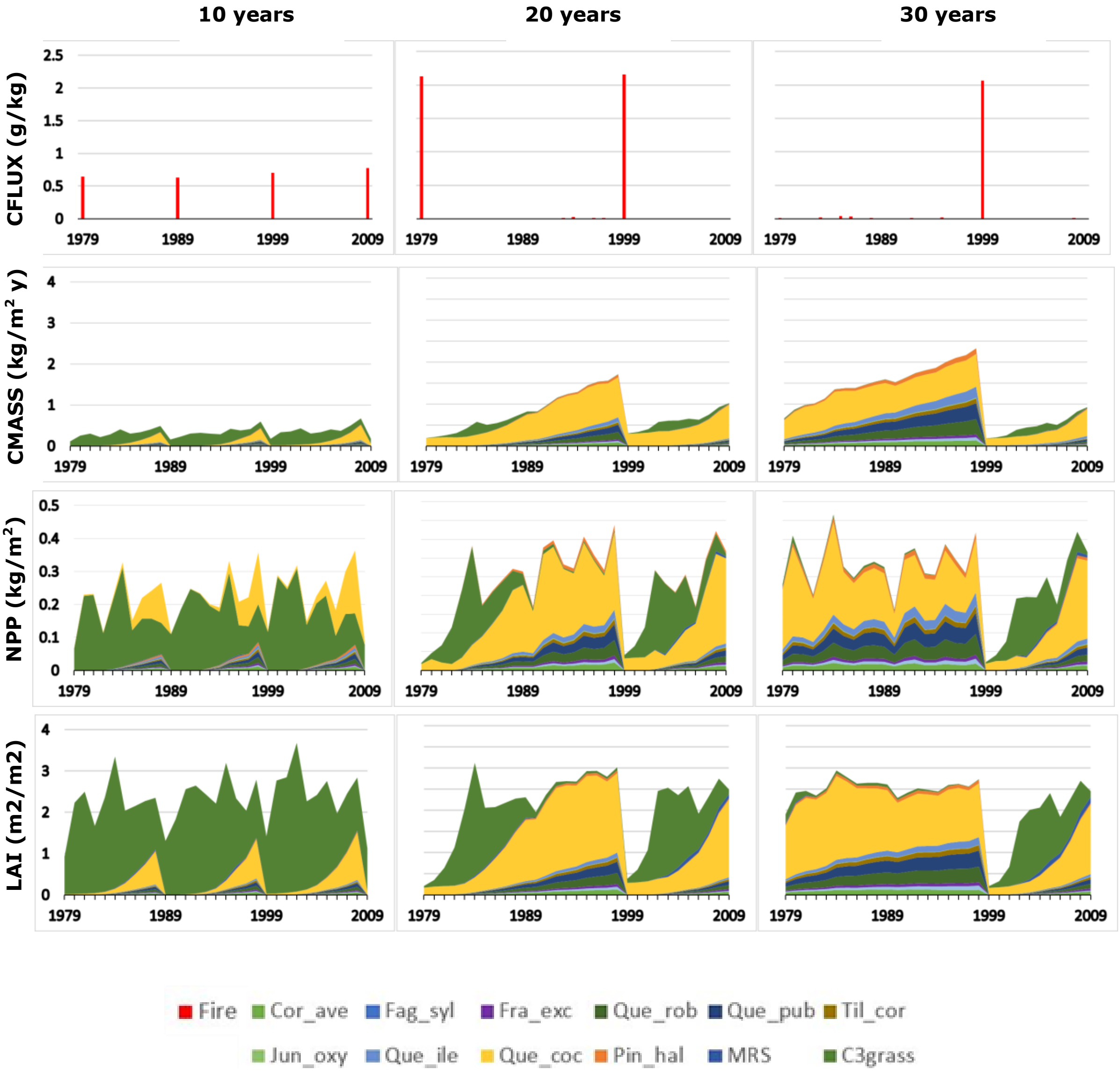


Figure 11. CMASS, NPP and LAI within 10, 20 and 30 years fix fire return interval

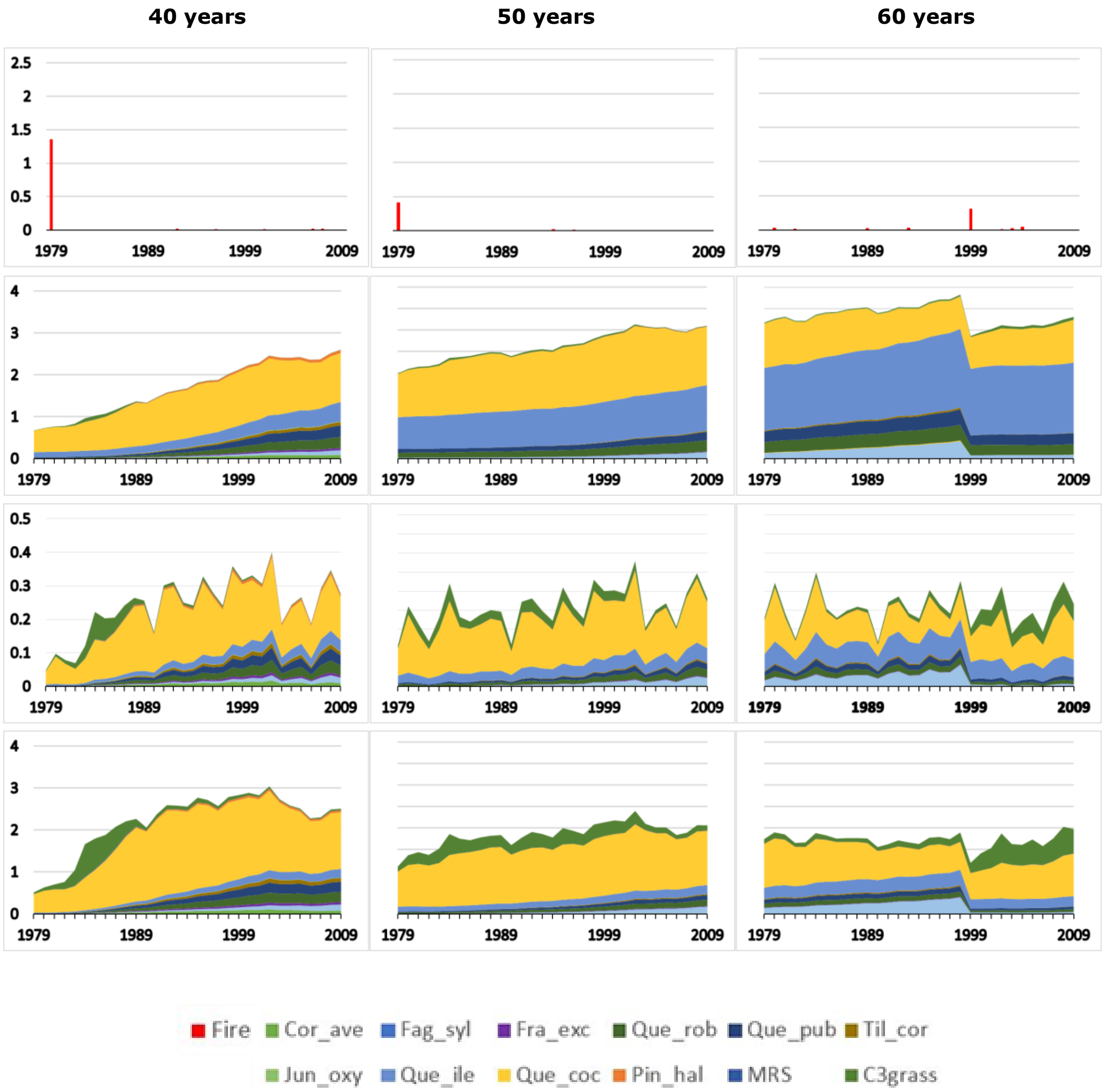


Figure 12. CMASS, NPP and LAI within 40, 50 and 60 years fix fire return interval

The results suggest great facility of establishment for non-woody species within short fix fire return intervals. Grasses C3 at first and *Quercus coccifera* subsequently, appear predominantly under such kind of successional stages. On the contrary, woody species like *Quercus Ilex* barely appear in these conditions. It would seem that under such higher recurrence fire interval, they need more time to settle. An increase of 30 years fix fire return interval brings a new successional scenario. Although *Quercus coccifera* is still predominant, *Quercus Ilex*, *Quercus pubescens* or *Quercus robur* begin a partial colonization of the patches. The PFT show high resilience/sensitivity to fire events since LAI, CMASS and NPP decrease abruptly after disturbance. Moreover, an immediate increase in grasses and *Quercus coccifera* is estimated after fire occurrence.

However, woody species show a much higher tendency to establish within 40 fix fire return intervals. *Fagus sylvatica*, *Tilia cordata* and *Pinus halepensis* behave as the previous mentioned species. The weight of these PFT in the ecosystem increases at the same time as the fire regime experiences higher gaps between fix fire return intervals. 50 and 60 years simulations shown how woody species are highly more prominent than shrublands or grasslands. *Fagus sylvatica*, *Quercus Ilex*, *Quercus pubescens, Quecus robur* together with *Quercus coccifera* in a lower extent, are predominant.

Additionally, individual remarks to each thematic outputs are presented. CMASS seems to follow an homogenous increase in comparison with the oscillating behaviour previously shown by NPP along the time. An example of the first is the smooth and fluent increase of biomass from 30-40-50 to 60 years of fix fire return interval's series. On the other hand, NPP fluctuates relatively often and such behaviour could be caused by the seasonal and inter-annual weather's variability experienced by the vegetation. Unexpected results were simulated regarding the fires within 40-50-60 years fix return interval. The intensity of the fires seems to decrease with respect to the increased fire recurrence. Only one big fire has occurred along 40 years' case. The following two (50 and 60 years fire recurrence) show a significant decrease of the emissions.

4.1.2. Code modification in LPJ-GUESS-SPITFIRE

Fire behaviour outputs from SPITFIRE were tested in order to be compared with the simulations based on FARSITE. ROS, IR, HPA, FLI and FML were assessed along 100 patches, fire ignited 1st of August 2004 under 25 years fix fire return interval. Preliminary calculations based on Rothermel's equations showed an apparent downward trend derived from LPJ-GUESS-SPITFIRE simulations. These pilot results evidenced an underestimation in comparison with values described by Albini in unpublished training notes (Pyne et al. 1996), but also with typical ranges of fire behaviour variables measured in the field along Mediterranean areas (Santoni et al. 2006; Silvani and Morandini 2009).

No major changes were found regarding the fire behaviour variables calculated (Figure 13 and 14) from both alternatives of the code. Shapiro-Wilks test with regards to normality have shown very low p-values. This p-value relates to the probability that the tested samples follow a normal distribution. The lower this value, the smaller the chance. Since all of the p-value tested were lower than 0.05, it was assumed that data-sets deviate from normality. Therefore, non-parametric U-test analysis was applied.

Results from Wilcoxon Mann-Whitney Test are given in the Table 3. ROS, IR, FLI, FML and HPA resulted in p-values >0.05, hence the null hypothesis was not rejected. There is not enough evidence that both distribution function and mean are not statistical alike.

	ROS	**IR**	**FLI**	**FML**	**HPA**
p-value	0.9376	0.7638	0.8748	0.8545	0.6672

Table 3. Wilcoxon Mann-Whitney Test: Code's modification in LPJ-GUESS-SPITFIRE

Generally speaking, distributions from both populations (100 samples each one) tend to be skewed to the left (i.e. mode< median <mean). The amendments in fire.cpp code regarding effective heating and heat of pre-ignition parameters slightly increased mean values such as ROS from 0.3 ± 0.2 m/min before had introduced any change to 0.4 ± 0.6 m/min subsequently , IR from 329.5 ± 128.2 kW/m2 to 336.2 ± 131.9 kW/m2 and 46.2 ± 53.8 to 47 ± 76.9 in the case of FLI. The effect of the observed outliers has spread out the respective distributions. In the case of flame length, both mean and standard

deviation remain identical, i.e. 0.4 ± 0.2 m. In contrast, the HPA mean value decreased from 2607.5 ± 1837.1 to 2413.9 ± 1247.5 kJ/m2. The variable tends to be less spread distributed compared with ROS, FLI or IR. This is also translated into lower estimated maximum values.

The initial assumption hypothesized a decrease of FLI and FML in case the ROS could decay. In fact such variation did not take place. Similarly befalls with HPA, dependent on IR.

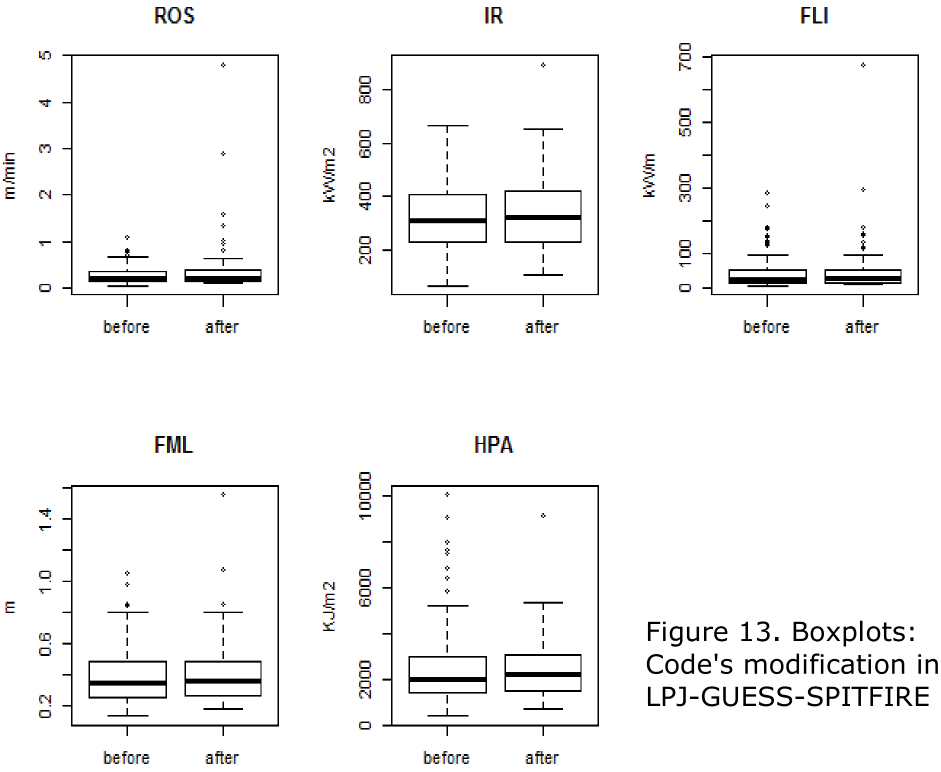


Figure 13. Boxplots: Code's modification in LPJ-GUESS-SPITFIRE

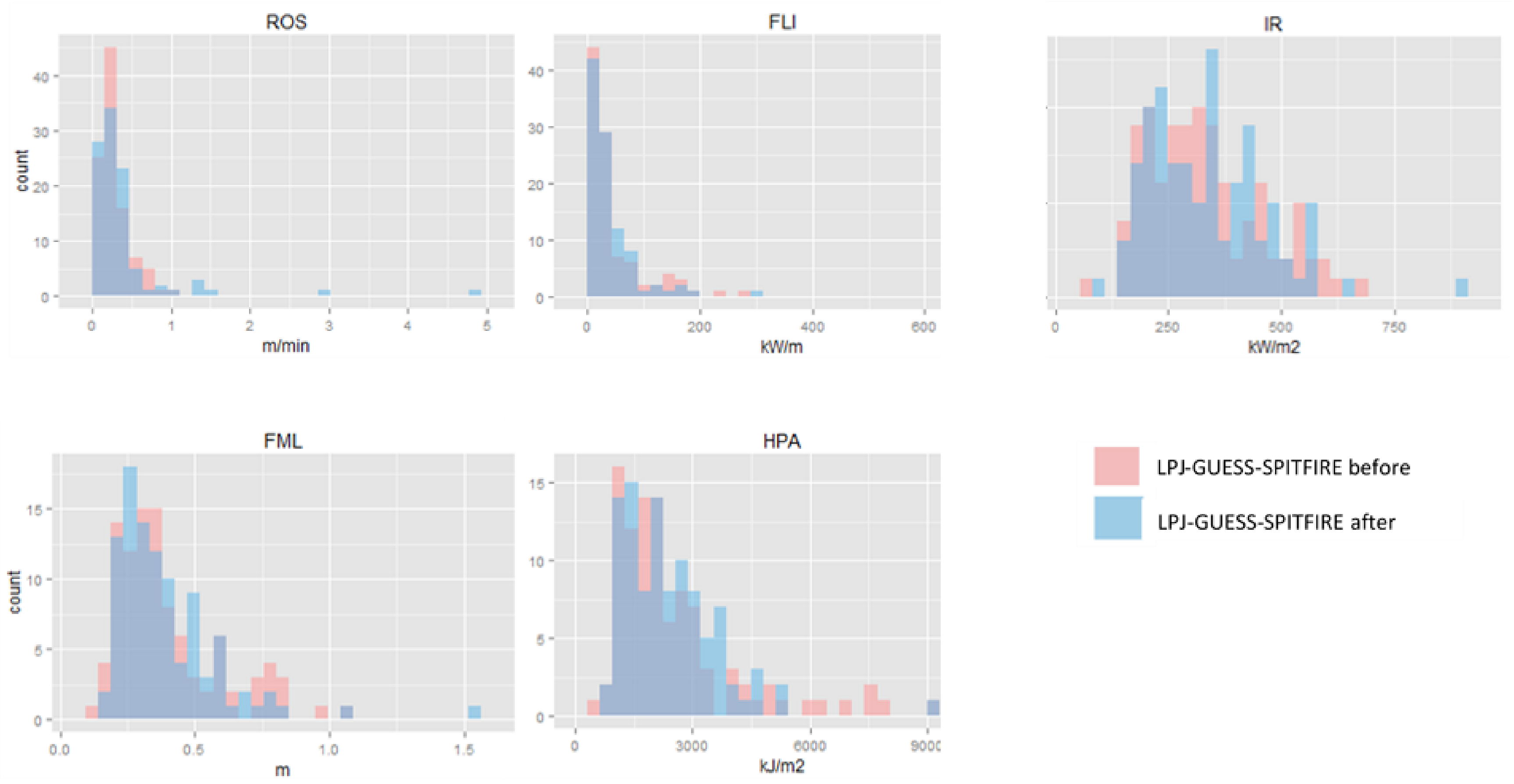


Figure 14. Performance differences for ROS, FLI, FML, IR and HPA represented as changes in histograms due to code's modification in LPJ-GUESS-SPITFIRE

4.2. Comparison between models: LPJ-GUESS-SPITFIRE vs FARSITE

4.2.1. Fuel and tree-related characteristics

Outputs related to fuel and tree characteristics generated by LPJ-GUESS-SPITFIRE have been compared against field data-set collected in the study area. Three different themes were evaluated: fuel models, fuel moisture and standing tree parameters. Generally speaking, fuel loading tends to be underestimated in LPJ-GUESS-SPITFIRE, hence fuel depth and moisture of extinction led to low values. Fuel moisture 1h and live-grass have been estimated downward as well. In contrast, dead fuel moisture 10h and 100h have shown an overestimated trend in comparison with standardized fuel moisture scenarios proposed in FARSITE.

Table 4 shows, firstly, custom fuel model from Provence region and secondly, Table 5, results calculated from LPJ-framework. Even though 11 different PFT were present in the first instance (C3_grass, Cor_ave, Fag_syl, Fra_exc, Jun_oxy, MRS, Pin_hal, Que_coc, Que_ilex, Que_pub, Que_rob, Til_cor), most of the values simulated were significantly low. Therefore, PFT with fuel loading 1h < $1e^{-3}$ T/ha and fuel depth < 1 cm were neglected in the comparison.

C3 grasses, *Quercus coccifera* (25 and 50 years fire recurrence) and *Quercus Ilex* (50 years) have been selected. C3 grasses correspond to HEA custom fuel model, whereas Quercus coccifera relates to MAQ. The tendency of fuel loading is clearly downward when it comes to LPJ-based estimations. *Quercus coccifera* (25 years) fuel loading and fuel depth simulation are the closest values to the field measurements. Both models agree in dead fuel loadings 10h and 100h for heathland/grasses. This vegetation type remains too thin, hence only dead 1h and live-grass fuel loading are present. However LPJ performs from 1 to 2 orders of magnitude less than the data collected. Unexpectedly, an increase of fuel loading 10h and 100h after fire event was noticed, contrary to the reasonable decrease of fuel loading 1h (see Annexe 7.10). This is due to the mortality of woody species. Once the trees are killed, branches and trunks become fuel loading 10 and 100 hr.

Low values of fuel loading lead to underestimation of fuel depth and Mx since both are fuel loading-dependents. Fuel depth records do not follow the same homogeneity as fuel loading along the time. There are years with either very low or directly no-fuel depth at all (probably due to the impact of fire events). Moisture of extinction estimations, on the other hand, seem unrealistic because a litter flammability moisture factor of 20% was assigned to grasses and a 30% to shrubs and forest. The results only indicate reasonable ranges of performance (i.e. 20-30% Mx) if there is enough fuel loading, otherwise it leads to unviable values.

Fuel moisture shows a different behaviour compared to preceding variables. LPJ-GUESS-SPITFIRE tends to overestimate fuel moisture 10h and 100h compared to FARSITE fuel models. Nonetheless, fuel moisture 1h and live grass have shown very low moisture instead, almost null. Although zero is an overstatement, it seems reasonable due to high dryness performed by the model in summer periods.

Tree related parameters take into account vegetation cover, i.e. foliar projective coverage for grasses and trees, together with tree height and crown height. An overview between models is presented in Table 6. MAQ and Que_coc show a notable agreement regarding the associated tree variables. Meanwhile HEA and C3_grasses count null tree and crown height as expected (life form grass is different than life form tree or shrub). However, canopy cover differs. LPJ-GUESS-SPITFIRE provides the equivalent of canopy cover for grasses. FARSITE does not take it into account, and for this reason it remains as zero. DFOR and Que_ile displayed the highest disagreement. A canopy cover of 70% introduced by FARSITE data-set opposed the scarce 5% calculated by LPJ. Even though the calculations of fix fire return interval are set to 50years, the underestimation seems obvious. Tree and crown height estimated in LPJ are also higher than in observations. Nonetheless, the results are not clear if the vegetation type is miscellaneous/mixed.

Table 4. Custom fuel model collected from Provence region

Vegetation Type	code_FM	Soil	Fuel Model	Fuel load ($t.ha^{-1}$)				Depth (cm)	Mx (%)	Initial DFMC (%)			LFMC (%)	
				1h	10h	100h	live			1h	10h	100h	H	W
Heatland	21	Ca/Si	**HEA**	0.45	0	0	2.58	27.00	30.00	9.00	10.00	11.00	80.00	90
Scrub	32	Si	**MAQ**	3	0.8	0.1	3.2	80.00	20.00	9.00	10.00	11.00	80.00	90
Scrub woodland	33	Si	**WMAQ**	3.8	0.9	0.2	3.2	220.00	20.00	9.00	10.00	11.00	80.00	90
Coppice	24	Ca/Si	**COP**	6	1.5	0.3	3.57	53.00	28.00	9.00	10.00	11.00	100.00	120
Conifer over coppic	26	Ca/Si	**CCOP**	8.4	1.05	0.39	1.69	33.00	25.00	9.00	10.00	11.00	100.00	110
Decideous forest	37	Si	**DFOR**	7	1.8	0.3	3	10.00	25.00	9.00	10.00	11.00	100.00	120
Coniferous forest	38	Si	**CFOR**	6.75	1.13	0.27	2.6	10.00	23.00	9.00	10.00	11.00	100.00	120
Mixed forest	39	Si	**MFOR**	7.65	1.13	0.27	3.47	10.00	25.00	9.00	10.00	11.00	100.00	120
Non burnable	99													

* Heat content=18000 kJ/Kg for all fuel models

Table 5. Custom fuel model generated by LPJ-GUESS-SPITFIRE

	Vegetation Type	code_FM	Soil	Fuel Model (PFT)	Fuel load ($t.ha^{-1}$)				Depth (cm)	Mx (%)	Initial DFMC (%)			LFMC (%)	
					1h	10h	100h	live			1h	10h	100h	H	W
25y	**Temperate grasses**	1	-	**C3_grass**	0.43	0.00	0.00	0.0039	4.30	2.60	21.45	100.00	100.00	7.17	-
	Temperate shrubla	2	-	**Que_coc**	1.84	0.22	0.78	0.0000	28.31	24.57	0.00	43.10	30.77	-	-
	Temperate grasses	1	-	**C3_grass**	0.49	0.00	0.00	0.0040	4.94	2.54	22.85	100.00	100.00	6.76	-
50y	**Temperate shrubla**	2	-	**Que_coc**	1.57	0.14	0.52	0.0000	22.36	17.83	0.00	50.31	37.32	-	-
	Temperate forest	3	-	**Que_ilex**	0.18	0.05	0.17	0.0000	4.08	3.61	1.82	72.87	61.33	-	-

* Heat content=18000 kJ/Kg for all fuel models

Table 6. Tree-related variables comparison

	FAR	SPIT	FAR	SPIT	FAR	SPIT
	HEA	C3_grass	MAQ	Que_coc	DFOR	Que_ilex
Canopy cover (%)	0	10.48	5	6.64	70	5
Tree height (m)	0	0	4.5	2.12	9.5	11.24
Crown height (m)	0	0	1.5	0.71	1.5	3.74

4.2.2. Fire behaviour performance

The distribution for each fire behaviour output simulated both from LPJ-GUESS-SPITFIRE and FARSITE have been plotted comparing their modelling performance. ROS, IR, FLI, HPA and FML are represented in Figure 15 and 16. Results derived from LPJ-GUESS-SPITFIRE present an underestimation pattern all over the variables in comparison with FARSITE. Under analogous topography and weather influence, only fuel- and tree related variables (i.e. fuel loading, fuel depth, fuel moisture canopy cover, standing tree and crown height) differ over the assessment.

Results from Shapiro-Wilks test suggest both FARSITE and LPJ-GUESS-SPITFIRE populations deviated from normality (p-value < 0.05). Furthermore, ROS, IR, FLI, HPA and FML derived p-values <0.05 from Wilcoxon Mann-Whitney Test (Table 7), hence the null hypothesis was rejected. There is enough evidence that both distribution function and mean are not statistical identical.

	ROS	**IR**	**FLI**	**FML**	**HPA**
p-value	< 2.2e-16	1.42E-13	< 2.2e-16	< 2.2e-16	< 2.2e-16

Table 7.Wilcoxon Mann-Whitney Test: LPJ-GUESS-SPITFIRE vs FARSITE

Mean values calculated by FARSITE are significantly higher. The range of dispersion derived is also wider than the simulated by LPJ-framework (figure 13). The spread of ROS, FLI, IR and FML between 1st Quartile and 3th Quartile (50% of the population) is considerably much higher in FARSITE than in SPITFIRE. This difference in performance is most likely originated by the influence of fuel and tree- related input variable used.

ROS experienced a fire spread range from 0.1 to 4.8 m/min in SPITFIRE while FARSITE accounted records of up to 7.4 m/min. The mean value calculated by FARSITE is relatively higher in comparison with the results obtained from SPITFIRE. The distributions show 3.5 ± 0.1 m/min and 0.4 ± 0.1 m/min respectively. Both models show a higher amount of counts under low ROS (i.e. < 1.0 m/min).

In the case of IR, the histogram plotting FARSITE calculations shows a core with many of the pixel counts presenting high intensities. As a result, FARSITE's mean and standard deviation values (780.2 ± 451.2 kW/m^2) overestimate substantially the ones from LPJ-framework (336.2 ± 131.9 kW/m^2). However, IR shares more common counts from both models than any other fire behaviour variable assessed (especially within the range 100-400 kW/m^2).

SPITFIRE simulates FLI with values ranging from 6 to 674.3 kW/m. In contrast, FARSITE's results have fluctuated from 4.9 to 773.9kW/m. Similarly to ROS, the spreading of the distribution remains dispersed in comparison with SPITFIRE. FLI simulated in SPITFIRE reached a mean intensity of 47 ±76.9 kW/m against the 357.1± 231.3 kW/m calculated in FARSITE.

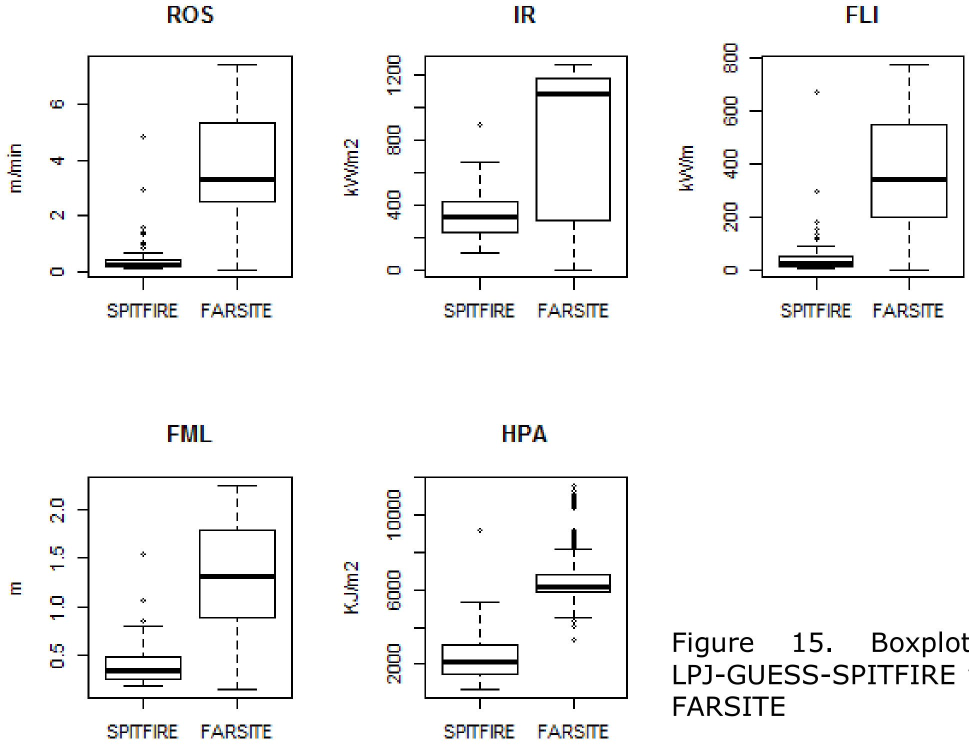


Figure 15. Boxplots: LPJ-GUESS-SPITFIRE vs FARSITE

FML fluctuated from 0.2 to 1.6 m based on SPITFIRE simulations against the 0.2 to 2.25 meters predicted by FARSITE. In terms of distribution's variation, FARSITE resulted in a 1.3 ± 0.6 m in comparison with only 0.4 ± 0.2m in SPITFIRE. Both models show partial agreement in FML lower than 0.5 m. However, SPITFIRE barely calculates lengths higher than 1 m in comparison with FARSITE.

FARSITE calculates much larger numbers regarding HPA. There is almost null agreement between models. For instance, the mean values range from 2413.9 ± 1247.5 kJ/m^2 in SPITFIRE to 6543.7 ± 1424.2 kJ/m^2 in FARSITE. The maximum estimations showed peaks of 9144 and 11568.9 kJ/m^2 respectively. Such difference in estimations exemplify the disagreement.

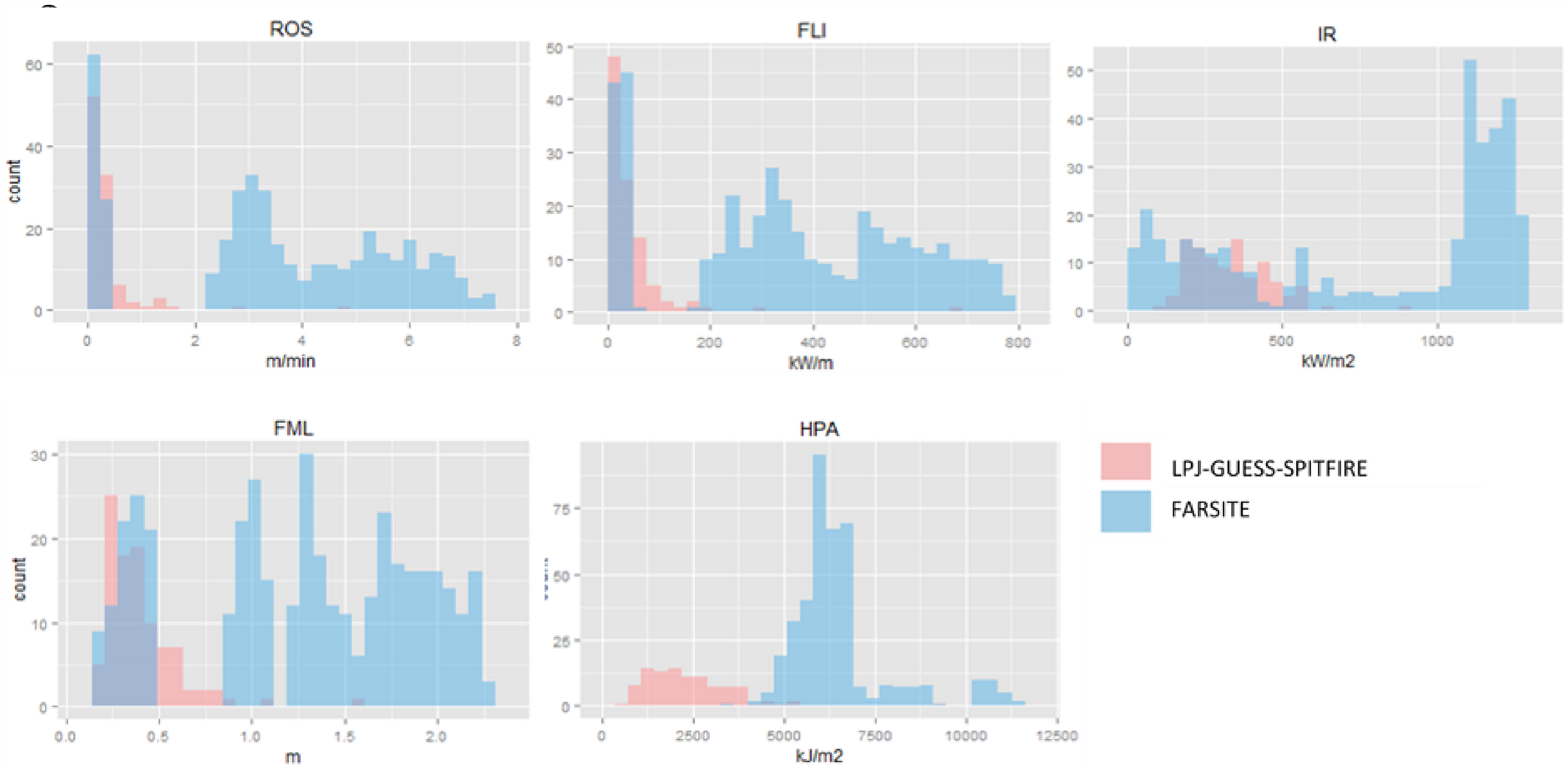


Figure 7. Performance differences for ROS, FLI, FML, IR and HPA represented as histograms: LPJ-GUESS-SPITFIRE vs FARSITE

4.3. Introducing LPJ-GUESS outputs as inputs in FARSITE: LPJ-GUESS-FARSITE's germ

The vegetation resulted from 100 patches simulated in LPJ-GUESS-SPITFIRE were incorporated as input data in FARSITE. This approach aimed at evaluating the model's performance under identical fuel- and tree-input conditions. The distribution for each output-variable simulated from SPITFIRE, FARSITE and LPJ-FARSITE was plotted in order to compare each individual performance. ROS, IR, FLI, HPA and FML are represented in figure 17 and 18. Generally speaking, the results derived from the embedded LPJ-GUESS-FARSITE presented a wider range of fire behaviour estimations all over the variables compared to LPJ-GUESS-SPITFIRE.

Results from Shapiro-Wilks test suggested both populations' model deviated from normality ($p\text{-value} < 0.05$). According to Wilcoxon Mann-Whitney Test, none of the variables evaluated resulted in p-values >0.05, hence the null hypothesis was rejected. There is enough evidence to state that both distribution function and means are not statistical identical.

The main distinctive trait observed is the slight increase of ROS, moderate growth of IR, FLI and FML together with an atypical very high range of HPA in comparison with LPJ-GUESS-SPITFIRE (results represented in figure 15 and 16). It is interesting to see how both models performed differently under the same set of input data, i.e. climate, topography and vegetation.

Fire spread presented a mean value of 0.7 ± 0.3 m/min. In no case ROS exceeds 2 m/min. The range of values are similar to LPJ-GUESS-SPITFIRE, although slightly higher. It is also evident the narrowed dispersion shape of the distribution.

LPJ-GUESS-FARSITE has moderately increased the range of mean estimation of IR, FLI and FML to 698.3 ± 223.2 kW/m^2, 150.7 ± 67.7 kW/m and 0.8 ± 0.2 m respectively. The cited distributions have shown a slightly higher spread due to the appearance of outliers, which led to maximum records of 1547.2 kW/m^2, 442.87 kW/m and 1.55 m length.

HPA is the variable with highest degree of change from model to model. Since the increment of IR was not that large, such range of values were unexpected, simulating even higher intensities than FARSITE's calculations. A mean value 11986.6 ±1289.4 kJ/m^2 contrasted with the only 2413.9 ± 1247.5 kJ/m^2 simulated by LPJ-GUESS-SPITFIRE.

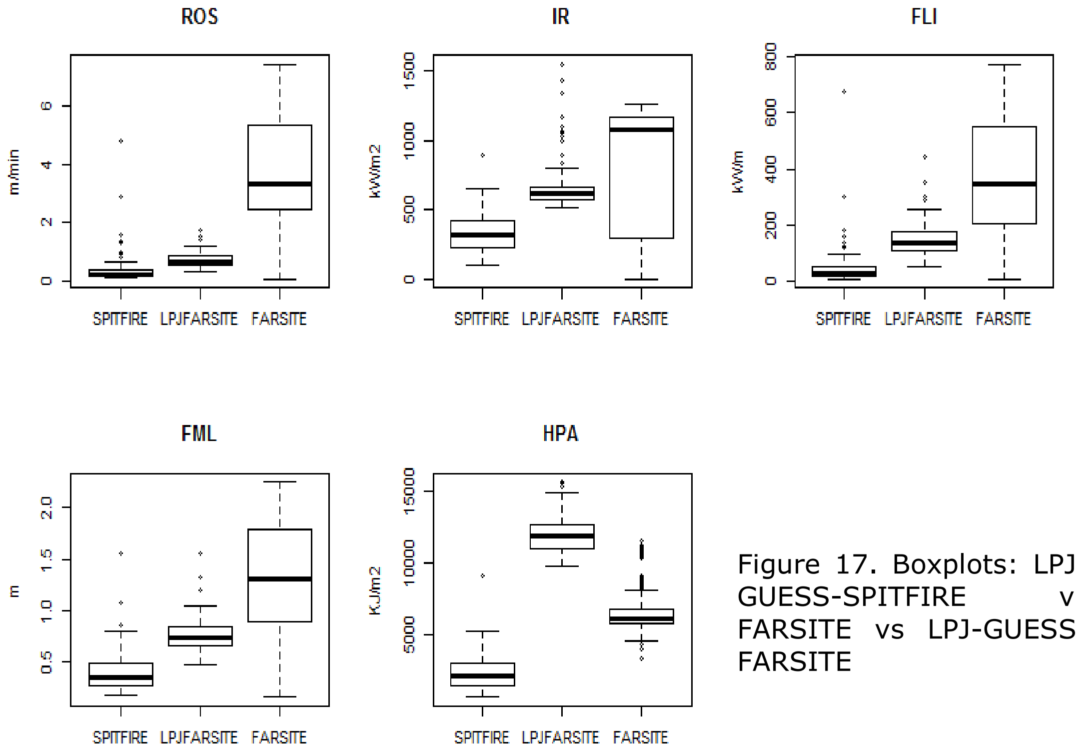


Figure 17. Boxplots: LPJ-GUESS-SPITFIRE vs FARSITE vs LPJ-GUESS-FARSITE

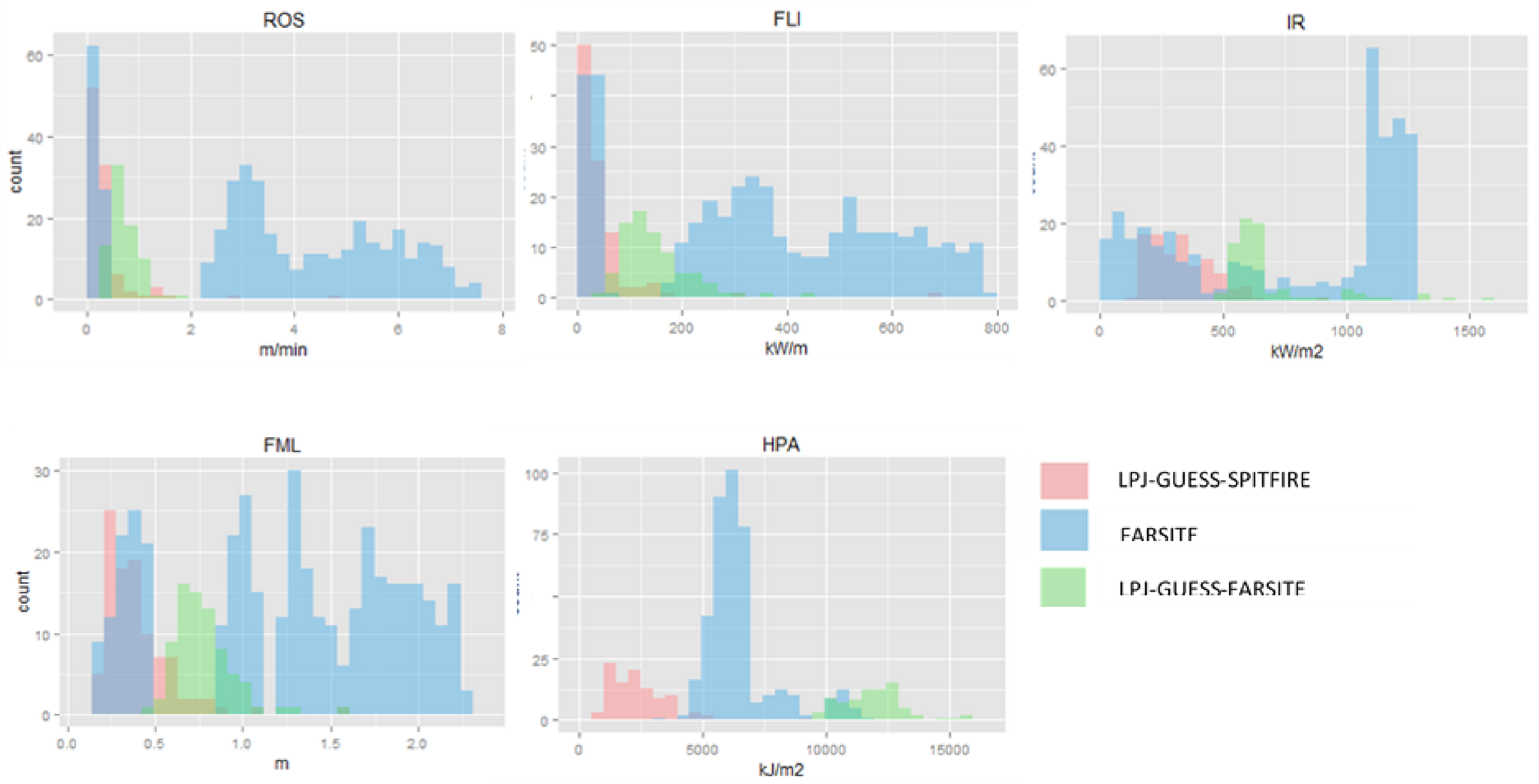


Figure 8. Performance differences for ROS, FLI, FML, IR and HPA represented as histograms: LPJ-GUESS-SPITFIRE vs FARSITE vs LPJ-GUESS-FARSITE

5. Discussion

In this section the results are discussed. The overall aim for this thesis was to assess a potential embedment of vegetation dynamics (LPJ-GUESS) into an explicit fire behaviour model (FARSITE). In order to do so, the main questions were focused on the possibility of LPJ-GUESS to simulate characteristic vegetation from Provence (France); how realistically both LPJ-GUESS-SPITFIRE and LPJ-GUESS-FARSITE performed fire spread as well as fire intensity-related estimations; and if any improvement could be made.

The following sections will go into further detail of (1) how initializers parameters have affected the presence/absence of the different PTFs; (2) how much fuel- and tree-related variables agree compared to field measurements; (3) how code's refinements have affected fire behaviour results; (4) how much agreement actually model comparison has shown, but also with field observations and finally, (5) some recommendations about how the models could be further developed.

5.1. Model's set up

5.1.1. Assessing initializers parameters at which LPJ needs to be run

Fire is a key disturbance factor in Mediterranean areas. Wildfire impacts and shapes the structure, composition and dynamics of the ecosystems (Pausas 1999). The existence of different fire return intervals (i.e. fire regimes or fire recurrence) led to different vegetation types in Mediterranean areas (Curt et al. 2011; Ganteaume et al. 2011; Schaffhauser et al. 2011; Schaffhauser et al. 2012a; Curt et al. 2013).

5.1.1.1. Fire return interval and succession stage

Generally speaking, fire affects directly the successional status of the ecosystem. More precisely, the cited change over the ecosystem is called secondary succession since the plants colonize an existing substrate after most or all biomass has been destroyed by a fire disturbance. Fire clears the patches (in LPJ-GUESS-SPITFIRE) or extensive areas (in real life) and resets succession locally. Furthermore it establishes new frames of competence between species. The strategies followed by rural species (R) (in frequently-disturbed environments) allow a more rapid adaptation to the ecosystem after disturbance than that of their competitors (C). An example is fire-prone areas, i.e. within fix fire return intervals lower than 20 years. It obstructs plant's survival due to insufficient time to recruit from seeds (Pausas 1999; Curt et al. 2009). Therefore, resprouting species such as *Quercus coccifera*, *Quercus Ilex* or *Quercus suber* is likely to see benefits under such conditions (Schaffhauser et al. 2011). In order to survive, plants need to adapt to the environment which surrounds them through the development of a specific strategy.

An expected (natural) sequence represents the replacement of R-type species (for example C3_grass) by C-type species at the same time that light, water and nutrient availability at soil surface declines. For instance, shade-intolerant pioneer trees (species like Cor_ave, Jun_oxy and MRS) can be initially established, followed by shade-tolerant trees afterwards (Car_bet, Fag_syl, Fra_exc, Que_rob, Que_pub, Til_cor, Que_ile, Que_coc and Pin_hal). According to Gordon (2008); Lehsten (2013); Schlesinger and Bernhardt (2013) changes in vegetation's structure and its stage within the succession directly affect functions such as NPP, LAI and CMASS. On the one hand CMASS tends to increase over time after the fire event, accumulating the biomass as sapwood and heartwood mass in tree stems/trunks. On the other, LAI and NPP tend to increase for the first few years but quickly saturate. The decrease in NPP is likely driven by the increased maintenance costs of old trees and (sometimes) reduced soil nutrient status. In fact, these different patterns fully agree with the results obtained (4.1.1). Short fire regimes lead to low CMASS together with high NPP and LAI. The tendency changes at the same time that fix fire return interval increases.

Schaffhauser et al. (2011) have assessed how the abundance/quantity and dimensions of trees and shrubs vary inversely to increasing fire return interval owing to selective mortality of trees. If fire recurrence increases, a reduction of the plant's vertical profile (i.e. tree height) together with canopy cover, stand basal area and litter depth can be observed. A complementary diagram supporting these relations is shown in Figure 19. Ganteaume et al. (2009) also suggested a significant reduction of canopy cover due to an increase of fire occurrences (i.e. decrease of fire return interval).

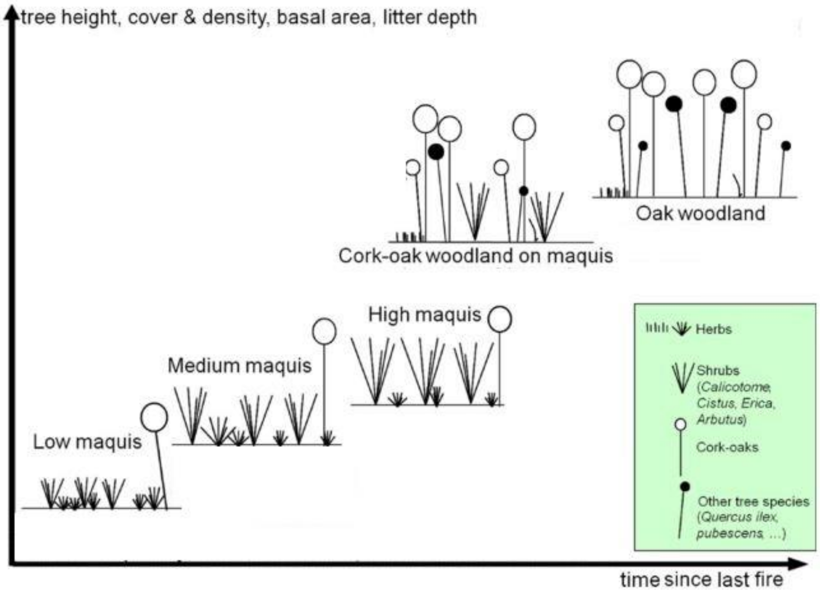


Figure 9. Succession stage dependent of fire recurrence (Schaffhauser et al. 2011)

Indeed, such behaviour can be elucidated from results simulated by LPJ-GUESS in comparison to figure 19. Within short fire regimes at early stages of succession only grassland (C3 grasses) and shrubland (*Quercus coccifera*) showed up. Estimations from the model suggested rather low woody biomass in overall terms together with high LAI and NPP from *Quercus coccifera* and C3 grasses under 10 and 20 years fix fire return intervals. Ganteaume et al. (2009) discusses the possibility of insufficient time from seed-producers species to restock seed bank. For instance, it could promote resprouting species such as *Quercus coccifera*, *Quercus Ilex* or *Quercus suber* (Pausas 1997; Delitti et al. 2005). *Quercus coccifera* has been described as a very fire-resilient plant specie, mostly due to its spread root system (Canellas and Miguel 1998). In Figure 19, cited resprouting species are represented by Cistus (medium maquis), Erica or Arbutus spp (both high maquis), homologue to *Quercus coccifera* in LPJ-GUESS. Opposed to these scenarios, 30, 40, 50 and 60 years show an increased weight of the woody species such as *Quercus Ilex*, *Quercus robur*, *Quercus pubescens*, *Pinus halepensis*, *Fagus sylvatica* and *Fraxinus excelsior.* The role of these PFT grows as return fire interval increases. *Quercus coccifera* and C3 grasses are still present but in much lower proportions.

5.1.1.2. Presence of PFTs

C3 grasses, *Quercus coccifera* and *Quercus Ilex* are three PFT representative of three different sequences of post-fire succession in Provence. The fact that C3 grasses and *Quercus coccifera* predominate at low fire intervals is consistent with observations on field. The optimum fire interval for these species has been found within 10-30 years from field studies. Woody types such as *Quercus Ilex* predominate at fire intervals > 30-50 years, so the results match field measurements (Schaffhauser et al. 2011; Schaffhauser et al. 2012b, a). Actually, in the eastern part of Provence, under similar conditions, *Quercus suber* grows instead of *Quercus Ilex*, and *Erica/Cistus spp* instead of *Quercus coccifera*. Curt et al. (2013) have summarized the main characteristic vegetation types with dominant species in the study area. Two different classifications exist depending on soil composition. However, LPJ-GUESS does not differentiate between either siliceous/acidic and limestone substrates. For instance, LPJ-GUESS seems to oversimplify vegetation types as well as it tends to model PFT as if the study area was in limestone-derived soils instead of over siliceous strata. One example, maquis vegetation type represented by *Erica arborea* and *Cistus spp* (what in theory belongs to MRS in LPJ) does not appear at all in the simulations. Instead, *Quercus coccifera*, typical example of garrigue vegetation type is widespread. Two possible explanations given to these facts could be: (1) *Quercus coccifera* is more competitive than MRS in conditions of water shortage and infertile soils and/or (2) the concept of PFT is too fuzzy for the level of detail required, i.e. a scale issue. Due to the mode of computation of LPJ-GUESS, the model does not differentiate between substrates at local scales. LPJ-GUESS is not suited for such detailed vegetation analyses since it is a global model. In case a complete substratum is not implemented, it could be considered that *Quercus coccifera* garrigue predominates everywhere (knowing that this will be in reality only on limestone), while the equivalent (*Erica/Cistus spp*) will be on acidic soils.

5.1.1.3. Positive feedback loop: vegetation-fire-vegetation

However, not only succession determines the establishment and structure of the vegetation. Since fire affects the vegetation in the past, the vegetation at the same time alters the fire behaviour of future fires generating a positive feedback loop. Ganteaume et al. (2011) suggest an increase in fire recurrence due to global climate change in the Mediterranean regions, hence it could derive in a structural simplification of the ecosystem. The cited global change can led to the establishment of new ecological situations, favouring desertification processes according to Vallejo (1997). Following the theory proposed by Malamud and Turcotte (1999), Schaffhauser et al. (2011) agreed on the fact that vegetation likely to have been affected by past fire events will also influence future fire behaviours by the plant’s successional stage. Therefore, initial areas dominated by woody species such as cork oak and high shrubs (advanced stages of succession) can lead to areas dominated by low and/or intermediate maquis (initial stage of succession) after intense and continued fires regimes. Acácio et al. (2009) have also reported similar results in Portugal. As reinforcement to this idea, an increment of shrublands was reported in the study area over the oak woodlands population as a consequence of traditional practices of abandonment and grazing (Curt et al. 2009). Once again, the risk of the fire evolves at the same time that fire recurrence decreases. Figure 20 exemplifies a hazard of burning at Maures massif using Weibull model with collected data from the field (Curt et al. 2013). The figure shows how the shrubs have higher hazard probability of being burned compared with woody species such as pine or oak.

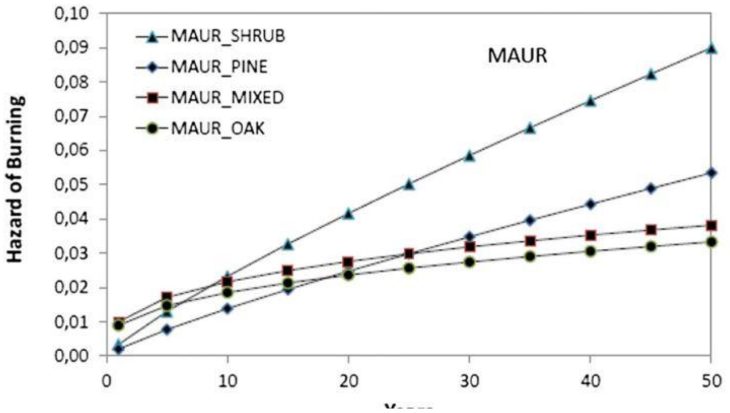


Figure 20. Hazard of burning [-] at Maures massif (Curt et al. 2013)

5.1.2. Code's modification in LPJ-GUESS-SPITFIRE: the before and the after

According to the fire behaviour parameterization prescribed by Rothermel (1972), subsequently revised in Albini (1976a), converted from English into SI units (Wilson 1980) and finally re-examined by Wilson Jr. (1982), part of the regular parameterization within fire module (fire.cpp) has not been properly formulated. On the one hand, Heat of pre-ignition's (Q_ig) equation clearly mismatches the equation shown in Thonicke et al. (2010). Although optimum packing ratio (beta_opt) uses the same parameterization in both code and journal article, the citations from the authors pointed out Wilson Jr. (1982) as parameterization's source in the other hand. Hence the evidence suggests a more than likely new typing error in the source code.

The modification of the code aimed at the improvement of LPJ-GUESS-SPITFIRE fire behaviour performance. However, the results did not suggest significant changes between ROS, IR, FLI, FML and HPA simulations, before and after the amendment.

Beta optimum is a parameter dependent on optimum reaction velocity which, at the same time, is a multiplier in the IR calculation. Therefore, beta optimum also influences ROS, FLI, FML and HPA estimations. On the other hand, the heat of pre ignition's parameter directly relates to ROS equation. Rate of spread is the key element in the calculation of Byram's Fire-line intensity, hence the flame length is, by extension, as well. However, the expected decrease in FLI, FML (caused by ROS,) and increase in HPA (forced by IR increment) did not occurred.

A possible explanation of such a slight difference in the results could be the minor weight of these two parameters in the overall performance of the fire behaviour parameterization. For instance, an upwards change driven by fuel loading or fuel moisture has readily shown apparent increased results (an example of fuel moisture influence is given in Annexe 7.11). Indeed, modifications in optimum packing ratio do not compute large differences since the modification falls into the order of thousandths. Nevertheless, an increment of two orders of magnitude within the heat of pre-ignition equation ought to derive into no trivial changes in ROS results, hence not affecting FLI and FML neither. The results do not shows such a difference. Perhaps the changes only motivated the appearance of spread peaks higher than 1m/min, increasing the variability of the simulations. The regular set-up of SPITFIRE has shown low and homogeneously distributed values of ROS below 0.5 m/min. Such low values are characteristic from areas without wind and slope influence (Pyne et al. 1996). Provence is characteristic for great influence of winds during the summer though (Curt et al. 2013).

FARSITE estimations were used as a benchmark in order to define what a reasonable output should look like. In addition Pyne et al. (1996), following Albini F.A unpublished training notes, also showed typical examples of ROS, HPA, FML and FLI under different conditions (Annexe 7.13). Both were used for preliminary comparison of the LPJ-GUESS-SPITFIRE's fire behaviour results. Already this first evaluation has shown certain signs of evident fire behaviour underestimation's tendency.

5.2. Comparison between models

5.2.1. Fuel and tree-related characteristics

The characterization of litter, and consequently fuel loading, as well as fuel depth and fuel moisture is essential for a fire behaviour assessment together with its effects (Pyne et al. 1996; Curt et al. 2011). The implementation of LPJ-GUESS-SPITFIRE's code allowed simulation of fuel related variables at the specific level of detail required to compare it with field measurements. Moreover, the development of such configuration also permitted a subsequent connexion to FARSITE as input data. In general terms, estimations have shown low fuel loading (Table 5), thus thin fuel depth. The simulations of fuel moisture show very low 1h and live grass moisture together with high 10h and100h fuel moisture (Table 5).

Nonetheless, with a suitable calibration of LPJ-GUESS-SPITFIRE, the model would allow the development of custom fuel model following a multi-temporal perspective. In particular, the current set up permits one fuel model per PFT per day of the year over 30 years' time sequence. Normally these fuel models are set for a specific time in specific circumstances. LPJ-GUESS-SPITFIRE offers an attractive dynamic sense into fire behaviour modelling.

5.2.1.1. Litter/fuel loading

A complementary comparison of custom fuel model CM28 developed by Salis (2007) from data set in North of Sardinia (Italy) has revealed a tendency to agree with respect to the fuel model developed in IRSTEA. Similar to Provence, Sardinia's typical vegetation is mostly based on Mediterranean shrub as well. Salis carried out field measurements in order to develop the custom fuel model; likewise, researchers in IRSTEA have developed the dataset used for this thesis. The performance of the cited fuel model against prescribed shrubland models from the US (Anderson 1982; Scott and Burgan 2005) was assessed. The best results were obtained with regards to the custom-homemade fuel model compared to the prescribed from US. The fuel loading and depth fuel from CM28 is in agreement with MAQ and WMAQ. Fuel loading 10h and 100h tend to be overestimated in CM28 though.

When comparing the mean values of LPJ-GUESS-SPITFIRE, the 1h and 10h fuel loads seem very low for Quer_ile (temperate forest) and Quer_coc (shrubland), and almost null for live fuel load whereas IRSTEA had measured values of ca. 3 T/ha. Likewise, a fuel depth of only 2.4 cm in forest seems very low (probably this is only litter) whereas researches carried out by IRSTEA generally have evolved in high fuel depth in the Mediterranean. The latter is mainly because many fuels are in understory (Ganteaume et al. 2009; Curt et al. 2011).

Litter derived from leaf and wood regarding *Quercus coccifera* annually simulated by LPJ-GUESS are extensively underestimated in comparison with observation from fieldwork carried out in Spain regarding the same specie (Canellas and Miguel 1998). Different litter fall rates were measured in 70, 40 and 10 years' fire recurrence dependent. Summing up leaf and wood litter, the study respectively obtained 381.2, 348.5 and 257.7 kg/ha year. LPJ-framework only simulated 173.61 kg/ha year for *Quercus coccifera*. This value also underestimates results obtained in France (Rapp and Lossaint 1981). On the other hand, typical litter fall rates in Mediterranean areas show 250-300g/m2 for *Quercus suber*, 250-700g/m2 for in *Quercus Ilex* whereas it is 400-500 for *Pinus halapensis* and 500-600 for Mediterranean decideous oaks. (Quézel and Médail 2003; Curt et al. 2011). For the given fire recurrence (25 years), LPJ-GUESS has estimated litter fall derived from woody species of < 1g/m2 in the same area. Therefore the downward tendency in simulating fuel loading and fuel depth evidence flaws in soil organic matter and vegetation dynamic modules instead of within the fire module. Litter inputs, generated in growth.cpp and introduced in fire module, are already low themselves.

The litter/fuel load of a specific area should not only directly relate to the vegetation established. The location can also vary the production-decomposition of combustible fuel (Olson 1963). According to Quézel and Médail (2003), litter biomass and fuel bulk density are the result from litter fall and its subsequent decomposition rate. Litter biomass, and for instance fuel load degradation, depends on the level of dryness, leaching, microbiological activity and/or fauna activity (Olson 1963; Wright 1997; Incerti et al. 2011).

Wright (1997) even has established a cause-effect relation between acidic/siliceous soils (i.e. low pH such as in Maures massif’s area) and lower decomposition/mineralization rates. This kind of soils has a characteristic small level of productivity and therefore a limited exchange of nutrients. In Provence acidic soils are more favourable to forest than limestone because they are a slight more fertile and have a bit higher water capacity and less stoniness (T. Curt, personal communication, 2014). This particular process was also noticed by Caritat et al. (2006) regarding low fuel loadings of Quercus suber over fertile soils.

In Wright (1997), dryness was also pointed out as an alternative disturbance’s source influencing production of litter/fuel. It was described how in Mediterranean areas, under water shortage/stress conditions, woody plants tend to present high concentrations of structural compounds (i.e. higher molecular weight particles) and low N content. This fact potentially could slow down decomposing rates (Castells et al. 2004; Incerti et al. 2011). More specifically, Wright (1997) associated high concentration of tannins in species to those better adapted to drought periods. Specifically, this was reported in sclerophyll plants such as *Quercus coccifera* and *Quercus Ilex*. As an example, *Quercus coccifera* presents a variable range of tannins, from 123 to 312 g/kg depending on the physiological scale.

Incerti et al. (2011) have related the overestimation of litter loss rate obtained in their simulations (i.e. underestimation of remaining leaf litter in the standing tree) with the abundance in inhibitory-structural compounds belonging to Mediterranean species. Therefore, higher molecular weight compounds such as tannins are most likely to lower organic matter decomposition and mineralization rates by forming organic matter-based complexes (Hättenschwiler and Vitousek 2000; Castells et al. 2004).

LPJ-GUESS takes into account carbon balance in the same way as biochemical cycle takes into account the litter decomposition processes. However due to the coarse scale, the models do not represent specific local conditions such as the Mediterranean region. Persson (2013) concluded that turnover times in LPJ-GUESS-SPITFIRE are not very representative for leaves and wood under specific local conditions. The current study has reproduced the same limitations.

For instance, if the cited decomposition rate of solid organic matter is set excessively fast (i.e. time of decomposition short), the fuel loading would lead to an unavoidable underestimation. In order to increase the fuel loading estimations, two different approaches could be applied:

1. A manual set up of the initialized file with one, and only one PFT per simulation, inducing the establishment of monoculture scenarios. Higher fuel loadings (up to 5 T/ha) and fuel depth are reached. Nonetheless, due to competition, species and functional types often have a more limited distribution than expected, based on their physiological limitations. For this reason the cited approach is rather unrealistic and its use in this thesis was ignored.
2. based on the causal relationship between the climatic/edaphologic conditions, and litter and soil organic matter decomposition (Incerti et al. 2011), LPJ-GUESS allows parameter tuning regarding turnover litter rates for leafs and wood. Simultaneously, regarding the use of PFT-specific routine (introduced in 3.3.3), the model performed higher fuel loading and fuel depth simulations. In LPJ-GUESS the relation of tau turnover times (years) for litter and soil organic matter at 10ºC are based on Foley (1995). The original values for tau litter leaf, root and wood (somdynamic.cpp) are all 2.85 for all PFT all over the world. The regular set up is rather simple and not representative of the reality. In case of an increment of tau_litter_leaf * 5 is applied, the results obtained reflect an

increase from 1.84 to 5.28 T/ha (fuel loading) and from 28.31 to 63.11 cm (fuel depth) regarding *Quercus coccifera* within 25 years fire recurrence.

5.2.1.2. Fuel moisture

Moisture models presented by IRSTEA remain in similar ranges with Salis (2007), agreeing in both low fuel moisture 1 h, 10 h and 100 h. The ranges stand for 10% 11% 12% and 8% 9% 10% respectively, i.e. vegetation is driven by water shortage conditions along the summer. Fuel moisture estimations are probably one of the weakest points of LPJ-GUESS-SPITFIRE. According to the results, obtained 1h-DFMC for temperate shrubland is very low (that mean complete desiccation), while 10h-DFMC of 43 to 100 among the fuel types indicates that they are rather fresh, which is never the case in Provence in summer. For instance, fuel moisture disagree considerably with the moisture estimated in Provence and reviewed by Salis in Sardinia. Indeed fuel moisture could be a key factor behind such low fire behaviour performance.

An interactive peer-review of LPJ-DGVM-SPITFIRE previous to its publication (Thonicke et al. 2010) exposed several discrepancies regarding fuel moisture performance. For instance, Venevski (2010) suggested flaws in simulation of fuel moisture. The author was also involved in the development of Reg-FIRM (Venevsky et al. 2002), a process based model which SPITFITE structure is mainly based on (i.e. similar approach and formulations such as Nesterov Index, Rothermel fire spread or natural/human ignition sources).

Venevski fully disagrees with the fuel moisture calculation, mostly regarding in two aspects:

1. The nature of the equation requires a drying rate (inverse proportions of three fuel classes’ SAV) in the order of 0.001 to 0.0001 to provide daily moisture higher than 50%. Venevski argued that, in terms of volume, the latter assumption represents a cubic fuel particle with SAV equal 1000 to 10000 respectively. Hence the fuel size would have either 0.006 to 0.00006 m (6/SAV). This theoretical framework leads to fuel particle too small. Even for a hypothetical higher fuel moisture, the particles sizes would be even smaller. The potential drawback over the

calculation would derive into most likely too dry fuel moisture. Indeed, LPJ-GUESS-SPITFIRE has calculated fuel moisture 1h and living grass for all PFT in null percentages (too dry). This fact also could be the reason behind fuel moistures around 100 % for PFT with extremely low fuel loads.

2. Daily fuel moisture is relatively possible error prone. Fuel moisture is calculated from the multiplication of inverse proportion of SAVs with densities of different fuel classes (1h, 10h, 100h) and Nesterov Index (all of them without well measured relative possible error). Then an exponential factor takes the product, which is possible error prone.

As a solution, Venevski suggested the introduction of dimension coefficients in the exponent based on non-linear regression from collected field data (fuel moisture and fuel loading). It was also even suggested the complete removal of the equation due to the importance of fuel moisture variable in the fire module. Since ROS, FLI and FML are dependent on fuel moisture, propagation errors are likely to be spread over simulations. An example of the influence caused by fuel moisture variability is shown in Annexe 7.11, where 9 different custom fuel models have been burned for testing purposes in a synthetic landscape.

5.2.1.3. Tree-related variables

Comparisons of tree-related variables have not shown critical disagreements, except for the canopy cover calculations. Since the very first simulations, LPJ-GUESS has revealed very low tree foliar projective cover. The vegetation coverage (canopy cover plus grass coverage) in the study area also has revealed relative low percentages (i.e. total vegetation cover< 20%). A possible explanation could be either (1) great level of dryness (2) incorrect /simplistic set up of soil types (particularly unfertile) or (3) potential error in the precipitation data from SQL database (since the precipitation is interpolated).

In the case of shrublands, if we compare Quer_coc estimations with MAQ they have both performed very similar. Indeed this shrub has been the finest PFT simulated by far within LPJ-framework in the study area. However, when comparing the forest species (i.e. DFOR vs Quer_ilex) IRSTEA has found very dense coppices cover with regards to *Quercus Ilex* in field measurements (coverage 30%)(Curt et al. 2011) while LPJ-GUESS calculated very low and resemble scattered individuals in 50 years fire recurrence (whereas in 25 years fix fire return interval remains almost null). Strictly speaking, *Quercus ilex* forests (which are more coppices with individuals of 5-8 m height) is not really a DFOR because *Quercus ilex* is sclerophyllous and evergreen (not deciduous) and not really a WMAQ (wooded maquis ~ shrubland with scattered oaks, from low to medium density). Probably the closed is however DFOR. This seems normal that it does not behave as WMAQ. IRSTEA have counted very few pure *Quercus ilex* forests in Provence, they are mixed with maquis, deciduous forests, or coniferous forests. The models reflect an issue of different conceptual framework of vegetation type from LPJ-GUESS and FARSITE when they couple. There are also discrepancies between HEA fuel model in FARSITE (0 %) and LPJ-GUESS derived coverage by grass (10.53 %). The most typical heathland of Provence is not covered with trees, but some mixed heathland (similar to the process of colonization by forest) can also have 1% of tree cover (T. Curt, personal communication, 2014).

On the other hand, the tree and crown height in Provence forests and shrublands are coppices of low height due to over-exploitation and severe drought. Also the unfertile soils of Maures massif landscape contribute to the cited tendency. For instance mean values calculated by LPJ-GUESS do not diverge unreasonably from the field measurements in the study area (Ganteaume et al. 2009). The estimations are not at maximum heights as could be expected for optimum conditions found in fertile soils (i.e. 30 for *Quercus Ilex* and 6 m for shrubs).

5.2.2. Fire behaviour parameters

5.2.2.1. Limitations

Even with the changes implemented over the Rothermel's equations in fire.cpp module, results from LPJ-GUESS-SPITFIRE vary largely in comparison with outcomes produced by FARSITE. These results presented a clear underestimation's tendency, which suggests the existence of certain variables directly affecting the low performance of the fire module.

In fact it was not unexpected to find out low values from calculated ROS, IR, FLI, FML or HPA in LPJ-GUESS-SPITFIRE after having analysed the global set of the framework. To the already mentioned flaws with respect to low vegetation cover, litter and fuel loading or uncertainty in fuel moisture's calculation, other important features related to fire behaviour must be added. Key parameters involved in fire performance were oversimplified or directly neglected:

1. Slope was not taken into account even though it is well known the sensitivity of wind over ROS calculated through Rothermel's parameterization or even measured in experiments (Pyne et al. 1996; Silvani et al. 2012). The authors themselves in Thonicke (2010) were aware about the limitations/consequences of leaving out the topographic component (i.e. underestimation-prone of burned area and ROS due to steep slope's influence). On the other hand the implementation of slope within a global framework is not trivial. Due to scale issues, the implementation of topographic variation in a DGVM is cumbersome and problematic. A 0.5º grid cell does not allow large slope's variations. Further experimentation in this direction is required.
2. Furthermore, the use of very simplified wind (only one measurement per day) has neglected daily variability and extreme high wind values. Once more the authors (Thonicke 2010) have claimed that the stated set up could lead to source of errors, most likely resulting into underestimation of ROS and burned area.
3. LPJ-GUESS only performs fire spread in short-lasting fires i.e. fires less than one day long. Thonicke (2010) indicated this is an improbable area, requiring further efforts in order to perform more realistic fire events during several days such as the implementation of over-night "stand-still".
4. Modifications in fuel loading derived from decrease in the soil organic matter decomposition (5.2.1.1) directly impacts in the severity of fire behaviour estimations. The more fuel loading the higher IRs and therefore the faster ROS, hence the higher HPA, FLI and FML ranges. If the uncertainties related to fuel moisture are added, the potential drawbacks are evident. In a framework where "Everything is connected" (Dopheide et al. 2012), a chain-effect easily could induce an error propagation from variable to variable causing questionable estimations.

Therefore, if there is an underestimation of fuel related-variables, fire behaviour variables are likely to increase more and more. In fact, the capability of LPJ-GUESS-SPITFIRE to perform reasonable ROS, IR, FLI, HPA and FML within an observed fuel loadings' benchmark allows the potential improvement of the model.

The reasons behind the apparent difference in performance between LPJ-GUESS-SPITFIRE and LPJ-GUESS-FARSITE (both performed under similar wind, weather and vegetation condition) remains less clear. Two reasons could influence such discrepancy: (1) FARSITE includes an acceleration model (figure 2), differentiating acceleration phase from quasi-steady-state; and/or (2) since FARSITE is spatial-explicit raster-based, the algorithms used for the fire spread's calculations differs from the point-based calculations followed in LPJ.

Additionally, there are uncertainties related to the fact that a fire model such as FARSITE, developed for local purposes, could be applied for much coarser resolutions. A sensitivity analysis of variable spatial resolutions would help to found out the actual impact over the model performance. This is a must before claiming that FARSITE is applicable to global fire modelling.

5.2.2.2. Validation

Fire collected data from real wildfires is scarce, rare to find in published literature and limited to a very specific weather- and fuel-related conditions. Therefore fire behaviour model's validation is cumbersome and challenging. Either an accurate spatial or temporal validation with regards to Earth Observation data is difficult due to the smooth resolution required for this study. For this reason a range of typical fire behaviour measured in laboratory and field plots with well documented fuels, topographic characteristics and weather conditions were preferred. The observed data belongs only to typical Mediterranean ecosystems (i.e. Provence, Sardinia or Corsica) aiming at environment conditions such as climate and equivalent range of vegetation as close as the ones found in Provence.

Laboratory-based fire spread experiments as well as litter flammability measurements have been performed in the past (Cheney and Gould 1995; Curt et al. 2011; Ganteaume et al. 2011; Silvani et al. 2012). However, this kind of measurements are only indicative/circumstantial due to the simplification of the either (1) temporal and spatial scale, (2) front-fire intensity and heat transfer performance (Silvani and Morandini 2009), (3) potential underestimation of the turbulence produced by air flows (Morandini et al 2006), (4) the use of low fuel loadings (i.e. small samples) (Curt al 2011) or (5) the impossibility of reaching steady state phase (McAlpine and Wakimoto 1991).

Therefore a need for measurable and comparable data from field experiment was required in the last years (Cheney and Gould 1995; Santoni et al. 2006; Silvani and Morandini 2006). Even though experimental designs do not duplicate actual fires, they can be taken into account as a guideline either for tuning fire behaviour models and/or its fire model's validation. Furthermore simulations from FARSITE model compared with field observations in Mediterranean regions (Arca et al. 2005; Arca et al. 2007; Salis 2007) have been also considered in the comparison.

Morandini et al. (2006) and Santoni et al. (2006)for example have carried out an experimental design over *Olea Europaea*, *Quercus Ilex*, *Arbutus Unedo* , *Cistus monspeliens* and *Cytisus triflorus* (mostly based on shrublands) in the Southern coastal region of Corsica (France). These species match/approximate quite reasonably the characteristic vegetation covered in Provence. Moreover, the authors reported a range from 2 to 3 m height, together with canopy cover based on 15% upper shrub layer and a 5% grass cover. These characteristics do not diverge from the ones manipulated in the experiments proposed. Relevant conditions during the fire experiment are presented in Table 8 in comparison with the experimental set up of the simulations carried out in the thesis. An unusual wet spring leads to high fuel moisture composition, which most likely could have affected the experiment. Moreover, the so called steady state was not reached due to the successive changes in wind direction and the heterogeneity of vegetation (i.e. even more intense fire behaviour could be reached).

	Morandini et al. (2006) and Santoni et al. (2006)	**Thesis' experiment**
Day	2nd July	1st August
Temperature	28°C	23.22°C
Cloudiness	free cloud	10%
Wind speed	4.2 (mean) m/s	1.81 m/s
Humidity (rel)	53%	65.89%
Slope	varying	0

Table 8. Comparison of conditions during simulations and the field

The authors have measured ROS values ranging from 6 to 24 m/min, significantly higher than the simulated by the models evaluated (See chapter 4.2 and 4.3). The novelty of these studies remains in the attempt of measuring heat release rates in situ. Even though severity of fire is best described by IR, it seems to be quite difficult to measure in field due to instrumental/technical limitations in real conditions regarding fire behaviour (Silvani and Morandini 2009). A new approach based on heat fluxes measurements from flame front was introduced due to how closely this parameter are linked to fire spread and heat release (Morandini et al. 2006; Santoni et al. 2006; Silvani and Morandini 2009). However it cannot be directly compared with IR. Heat fluxes measure the amount of heat reaching up to a target from the fire. The difference is IR quantifies the emission of heat, whereas the radiant heat flux is the result of the transport (i.e. heat flux densities (radiation) impinging ahead of the flame front when the sensor is outside of the flame). According to Santoni, it can be modelled the heat transported by radiation ahead of the fire front, knowing the amount of heat emitted by the source (X. Santoni, personal communication, 2014). Radiation represent about 30% of the total reaction intensity emitted by the flame (F. Morandini, personal communication, 2014). In the cited field experiments the range of Radiant heat flux has been estimated from 4000 to 8000W/m2 and 2000 to 4500W/m2 respectively and measured 5m far from fire.

Highest peaks qualified due to wind effect/disturbance, corresponding also to the highest flame lengths. The authors calculated FML using two different procedures: (1) based on mathematical equations derived from FLI (analogous to the ones used in this study) and (2) through a processing approach based on infrared image analysis according to Morandini et al. (2005). Both estimations give maximum flame lengths up to 7.5 m. To be more precise, the upper strata leads to mean flame lengths of 4 m whereas lower stratums lead to 1.3 m. These characteristic values of FML outnumber estimations from assessed models. Finally, FLI was calculated according to Byram (1959) showing peaks of 19000 and 20500 kW/m. In fact, the authors were aware about the potential overestimation in comparison with other studies referred to FLI measured on field. Nonetheless, authors also claim that, under attenuation fire-phases, FLI remains lower than 1000 kW/m. This range of Fire-line intensities are in tune with both literature and range simulated in the models.

In a like manner, Silvani and Morandini (2009) have also tested fire behaviour related variables in the characteristic Mediterranean region on the south of France (exact location was not specified). Target vegetation types were based on pine needles, oak branches, mix of oak and arbutus branches as well as shrubs. Typical characteristics from the field report fuel load measurements of 10 kg/m2 (=0.1T/ha) and mean fuel heights of 0.8 m. The experiment was performed over 20º slope and influenced by wind speeds of approximately 3.3 m/s. The field measurement has presented ROS of 10.8 m/min, mean FML of 7.2m and heat fluxes from 18000 up to 51000 W/m2. Once again the observations exceed the ranges simulated from models. According to the authors, the cited measurements are the most representative of real fire events occurred over Mediterranean shurbland.

The overall pattern of field measurements such latter described, denote a general trend to underestimate ROS, FLI, FML, IR and HPA in LPJ-GUESS-SPITFIRE, LPJ-GUESS-FARSITE models. FARSITE is likely to calculate closer ROS, IR, FLI, FML and HPA to field observed measurements though. Unlike FARSITE, LPJ-GUESS-SPITFIRE tends to estimate all of them downwards.

LPJ-GUESS-SPITFIRE or LPJ-GUESS-FARSITE calculations seem to have more similarities with experiments in laboratory, under conditions of lower fuel loadings, simplified wind influence or null slope impact, which limit the steady-state's reaching. For example, a flammability study in a laboratory was carried out by Silvani et al. (2012) in order to evaluate the influence of different slopes over ROS, FML and IR (radiant heat flux). Three out of nine experiments were executed in slope 0º (only these were utilized for the comparison). The fire behaviour variables resulted in ROS ranges from 0.79 to 0.83 m/min, FML of 0.99 m (indirectly calculated, given flame angle and flame height is possible to calculate FML through Pythagorean Theorem) and IR measures of 8 W/cm^2 maximum values. On the other hand, the results conducted by Curt et al. (2011) from a laboratory-based study in Provence found out even lower fire behaviour estimations (i.e. mean ROS = 0.74 ± 0.67 cm/s and mean FML =11.1±0.8 cm). Similarly, Ganteaume et al. (2011) have measured ROS 0.72 ± 0.47 m/min and FML 23.20 ± 13.77cm.

5.3. Recommendations

A series of recommendations are proposed for potential further implementation/ improvement within LPJ-GUESS framework:

- Before jumping over coarser scales, it is important to address correctly the local spatial variability of vegetation in different landscapes. A unique case study is not robust enough to conclude that LPJ-GUESS-FARSITE is better than LPJ-GUESS-SPITFIRE. Additional evaluations regarding models performance in different fire-prone ecosystems such as Spain, Portugal, Central Africa, US, Australia or Siberia are a must.

- The choice of 25 years fix fire return interval have most likely have limited the capability of other species to be present. Hence an analysis in depth of fuel-, tree- and fire behaviour-related variables under longer fire recurrence would allow the characterization of woody species as well.

- Subsequent implementations of variables demanded by FARSITE:
    - Surface-area-to-volume ratio for living grass and wood (cm^2/cm^3).
    - Explicit coarse woody model: diameter (cm), fuel loading (T/ha), heat content (kJ/kg), sapwood and heartwood density (g/cm^3) and moisture (%).
    - Canopy bulk density (Kg/ m3).
    - Explicit duff loading (T/ha).

- Since duff, canopy bulk density and coarse woody models were not assessed in the current study, a comparison of burning emissions was not taken into account. Lack in data related to post-frontal combustion led to unrealistic burning emission estimations. Post-frontal combustion's outputs (CO, CO_2, CH_4 or particulate material $PM_{2.5}$ and PM_{10}) can be directly compared between models.

- Revision in depth of the fuel moisture model based on Nesterov Index (Venevski 2010). Evaluation of additional moisture indexes such as Angstrom index, number of dry days or daily dry code (Chandler et al. 1983) or comparison with moisture data from field (relative humidity) would be recommendable. Fuel moisture is a key factor affecting ROS, FLI, FML, IR and HPA, hence special attention should be paid.

- An evaluation in detail of leaf turnover rates following Persson (2013)'s approach would led most likely into better representation of fuel-related estimations (hence also fire behaviour-related) in the study area.

- Slope has a direct impact over ROS estimations with regards to Rothermel's parameterization (Rothermel 1972; Pyne et al. 1996). A sensitivity analysis of slope & aspect & elevation effect is recommended. Fire behaviour could be assessed regarding the same data-set under the influence of changing topography, followed by a validation against experimental designs (Silvani et al. 2012).

- Analysis of the impact regarding limitations and assumptions prescribed from Rothermel's formulation.

- Assessment of exploratory future scenarios such as (1) potential vegetation changes derived from lower fire recurrence gaps,(2)the effect of increasing of shrublands cover over fire recurrence, (3) influence of either increasing temperature or decreasing precipitations over general fire behaviour.

- The first step was to situate LPJ-FARSITE "on-range", checking if it was close to reality. The next step would be to improve the accuracy. Increasing the spatial resolution, the inclusion of more detailed wind records (like computational fluid dynamic models) or the presence of slope would most likely contribute to more precise simulations (Arca et al. 2007; Salis 2007).

- To develop a meta-model for the fire model FARSITE connecting it to LPJ-GUESS. The typical LPJ-GUESS condition to be covered has to be simulated and a look-up table emerged from FARSITE have to be produced. Finally, LPJ-GUESS would read fire behaviour from the look-up table instead of from the SPITFIRE module.

6. Conclusion

The overall aim for this thesis was based on the assessment of a potential embedment from vegetation dynamics (LPJ-GUESS) into an explicit fire behaviour model (FARSITE). The case study area was centred on Maures massif, a characteristic landscape located in Provence (France). The study includes: (1) a comparison between vegetation simulated and vegetation observed in a Mediterranean region and, to what extent the fire recurrence affects vegetation; (2) the evaluation of fuel- and tree-related variables, comparing how close the vegetation modelled remains from the observed data and (3) the comparison of fire behaviour parameters such as ROS, IR, FLI, FML and HPA performed by LPJ-GUESS-SPITFIRE, FARSITE and LPJ-GUESS-FARSITE.

The first question (RQ 1) asked was if LPJ-GUESS-SPITFIRE represents the actual vegetation from Provence and if the fire return interval influences the ecosystem succession in the study area. The results have shown that *Quercus coccifera* and C3 grasses have been found to be predominant at 25 years fire return interval. On the other hand fire return interval largely influences the successional stage of the vegetation. Biomass tends to increase whereas leaf area index and net primary production decreases from short to long fire recurrence periods.

The second question (RQ 2) raised was if LPJ-GUESS-SPITFIRE gets similar fuel- and tree- related estimations from vegetation in comparison with data collected on the field along the study area. Dead fuel loading, fuel depth, fuel moisture 1h and live grass simulated in LPJ-GUESS-SPITFIRE tend to underestimate field measurements. On the contrary, fuel moisture 10h and 100h was found to be overestimated. The vegetation cover has shown relatively low mean values along the simulated 30 years (<20 %).

The third and fourth question (RQ 3 and 4) framed were if LPJ-GUESS-SPITFIRE and LPJ-GUESS-FARSITE respectively represent realistic and accurate fire spread as well as fire intensity. Fire behaviour results from both models have underestimated field experimental designs performed in similar conditions. FARSITE’s results, followed by LPJ-GUESS-FARSITE, have been closer related than LPJ-GUESS-SPITFIRE’s ones.

The fifth question (RQ 5) raised was if LPJ-GUESS-FARSITE perform better fire behaviour than LPJ-GUESS-SPITFIRE. In this study, even with identical weather conditions, null topography influence and identical input vegetation, the results presented evidences that LPJ-GUESS-FARSITE has calculated a higher range of ROS, IR, FLI, FML and HPA than LPJ-GUESS-SPITFIRE. For instance, LPJ-GUESS-FARSITE performs closer to field measurements.

This thesis exposes that the hypothesis that both FARSITE and LPJ-GUESS-FARSITE outputs are expected to be more realistic than LPJ-GUESS-SPITFIRE output have been confirmed. Even though results do still underestimate real observations, there is enough evidence to say that LPJ-GUESS framework could be improved. An increase in fire behaviour performance can be introduced from two different implementations. Firstly, the LPJ-GUESS-SPITFIRE’s source code modification due to either (1) the increase of litter and fuel loading, (2) decrease of fuel moisture or (3) incorporation of topographic variability. Secondly, through the complete substitution of SPITFIRE module by FARSITE model. The latter brings a variety of possibilities that in SPITFITRE would be more difficult to implement. When implementing FARSITE with its slope characterization and addition of maximum five weather and wind data sets with greater level of detail, the advantages in creating a meta-model are promising.

7. Annexes

7.1. Additional equations of fire spread.

Components of Rate of Spread	Formulation	Parameters
Heat required for ignition	$Q_{ig} = f\left(M_f, T_{ig}\right)$ $\varepsilon \equiv \frac{\rho_{be}}{\rho_b}$ $\rho_{be} = f\,(\text{bulk density}, \text{fuel size})$	Mf=ratio of fuel moisture to oven-dry weight T_{ig}= ignition temperature ε= bulk density-actual bulk density ratio
Propagating Flux	$I_p = I_{xig} \int_{-\infty}^{0} \left(\frac{\partial Iz}{\partial z}\right)_{z_c} dx$ $(I_p)_0 = R_0 \rho_b \varepsilon Q_{ig}$	R_0 = ROS with no-wind conditions $(I_P)_0$ = Basic heat flux component related to wind and slope
Reaction Intensity	$I_R = -\frac{dw}{dx} h$ $(I_p)_0 = f(I_R)$	$\frac{dw}{dx}$ = mass loss rate per unit area in the fire front h= heat content of fuel.
Effect of wind and slope	$I_p = (I_p)_0(1 + \phi_w + \phi_s)$	φ_w=Propagating flux by wind φ_s=Propagating flux by slope

Table 9. Additional equations of fire spread from Rothermel (1972)

7.2. Additional formulation describing elliptic spread's shape.

1.

Homogenous conditions	Formulation	Parameters
Without wind	$x = at\cos^2\chi$ $y = at\sin^2\chi$ $\sin^2\chi + \cos^2\chi = 1$ $x^2 + y^2 = a^2t^2$	x, y = coordinates in plane of a point in front of the fire a= rate of spread t= time elapsed since ignition. χ=angular coordinate which determine location of front fire
Constant wind	$x = at\,(f\cos^2\chi + g)$ $y = at\,(h\sin^2\chi)$ $\sin^2\chi + \cos^2\chi = 1$ $(\frac{x - agt}{aft})^2 + (\frac{y}{aht})^2 = 1$	f, g & h= wind's functions aft & aht= semi-axes of the ellipse ag= Speed of ellipse's centre at x-direction

Table 10. Additional formulation of wind effect from Anderson (1982)

2.

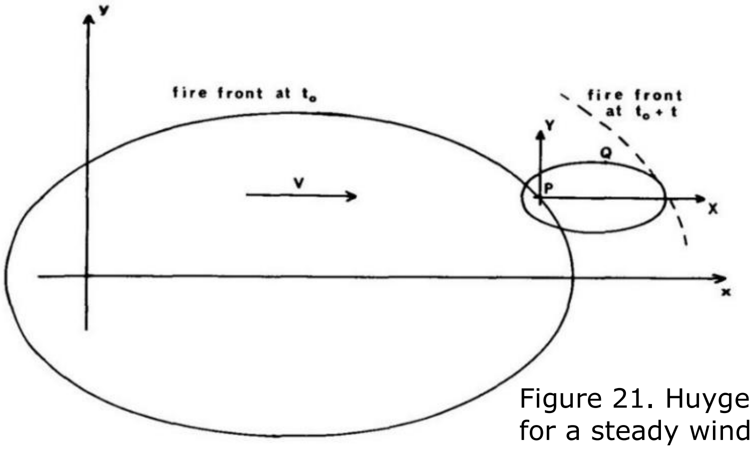
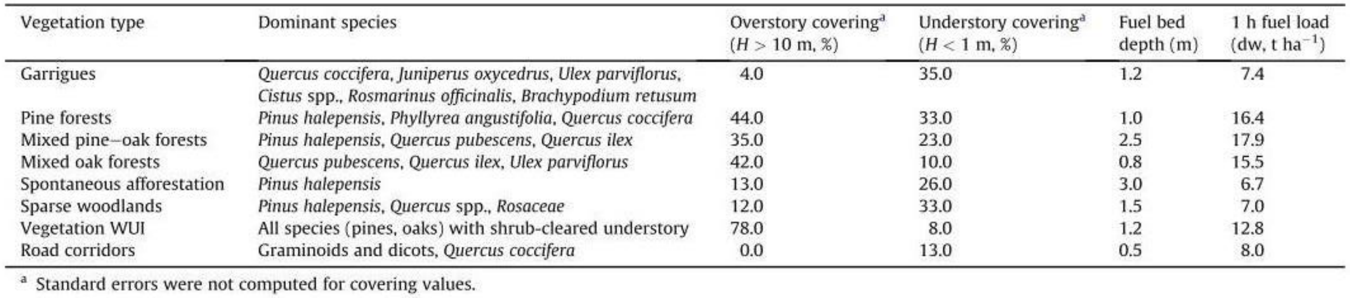


Figure 21. Huygens´ principle for a steady wind (V)

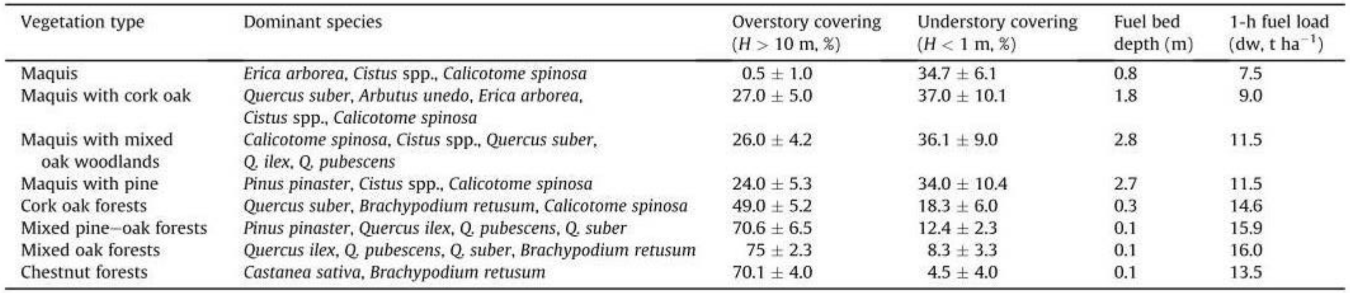
7.3. Main characteristics of the fuel types for the Provence region (Curt et al. 2013).



Vegetation type	Dominant species	Overstory covering[a] ($H > 10$ m, %)	Understory covering[a] ($H < 1$ m, %)	Fuel bed depth (m)	1 h fuel load (dw, t ha^{-1})
Garrigues	*Quercus coccifera, Juniperus oxycedrus, Ulex parviflorus, Cistus* spp., *Rosmarinus officinalis, Brachypodium retusum*	4.0	35.0	1.2	7.4
Pine forests	*Pinus halepensis, Phyllyrea angustifolia, Quercus coccifera*	44.0	33.0	1.0	16.4
Mixed pine–oak forests	*Pinus halepensis, Quercus pubescens, Quercus ilex*	35.0	23.0	2.5	17.9
Mixed oak forests	*Quercus pubescens, Quercus ilex, Ulex parviflorus*	42.0	10.0	0.8	15.5
Spontaneous afforestation	*Pinus halepensis*	13.0	26.0	3.0	6.7
Sparse woodlands	*Pinus halepensis, Quercus* spp., *Rosaceae*	12.0	33.0	1.5	7.0
Vegetation WUI	All species (pines, oaks) with shrub-cleared understory	78.0	8.0	1.2	12.8
Road corridors	Graminoids and dicots, *Quercus coccifera*	0.0	13.0	0.5	8.0

[a] Standard errors were not computed for covering values.

Table 11. Main characteristics of the fuel types in limestone-derived soils. Provence area



Vegetation type	Dominant species	Overstory covering ($H > 10$ m, %)	Understory covering ($H < 1$ m, %)	Fuel bed depth (m)	1-h fuel load (dw, t ha^{-1})
Maquis	*Erica arborea, Cistus* spp., *Calicotome spinosa*	0.5 ± 1.0	34.7 ± 6.1	0.8	7.5
Maquis with cork oak	*Quercus suber, Arbutus unedo, Erica arborea, Cistus* spp., *Calicotome spinosa*	27.0 ± 5.0	37.0 ± 10.1	1.8	9.0
Maquis with mixed oak woodlands	*Calicotome spinosa, Cistus* spp., *Quercus suber, Q. ilex, Q. pubescens*	26.0 ± 4.2	36.1 ± 9.0	2.8	11.5
Maquis with pine	*Pinus pinaster, Cistus* spp., *Calicotome spinosa*	24.0 ± 5.3	34.0 ± 10.4	2.7	11.5
Cork oak forests	*Quercus suber, Brachypodium retusum, Calicotome spinosa*	49.0 ± 5.2	18.3 ± 6.0	0.3	14.6
Mixed pine–oak forests	*Pinus pinaster, Quercus ilex, Q. pubescens, Q. suber*	70.6 ± 6.5	12.4 ± 2.3	0.1	15.9
Mixed oak forests	*Quercus ilex, Q. pubescens, Q. suber, Brachypodium retusum*	75 ± 2.3	8.3 ± 3.3	0.1	16.0
Chestnut forests	*Castanea sativa, Brachypodium retusum*	70.1 ± 4.0	4.5 ± 4.0	0.1	13.5

Table 12. Main characteristics of the fuel types in acidic-derived soils. Provence area

7.4. PFT characterized in LPJ-GUESS (2008 version). PFT present in Provence region (5º23’ E 43º2’ N).

PFT	Present	Group type	Important taxas (Spss)	Description
pLSE		Shrub	*Vaccinium, Erica spec*.	B, e
BES		Shrub	-	B, e, si
Bet_pub		Forest	*Betula pubescens*	B, b, si
Pic_abi		Forest	*Picea abies*	B, n, st
Pin_syl		Forest	*Pinus sylvestris*	B, n, ist
Bet_pen		Forest	*Betula pendula*	T, b, si
Abi_alb		Forest	*Abies alba*	T, n, st
Car_bet		Forest	*Carpinus betulus,*	T, b, ist
Cor_ave	X	Shrub	*Corylus avelans*	T, b, si
Fag_syl	X	Forest	*Fagus sylvatica*	T, b, st
Fra_exc	X	Forest	*Fraxinus excelsior*	T, b, ist
Que_rob	X	Forest	*Quercus robur*	T, b, ist
Que_pub	X	Forest	*Quercus pubescens*	T, b, ist
Til_cor	X	Forest	*Tilia cordata*	T, b, ist
Jun_oxy	X	Forest	*Juniperus oxycedrus*	T, n, si
Que_ile	X	Forest	*Quercus ilex*	T, b, ist
Que_coc	X	Shrub	*Quercus coccifera*	T, ist
Pin_hal	X	Forest	*Pinus halepensis*	T, n, si
MRS (S)	X	Shrub	*Cistus,Erica, Lavandula*	T, si
Pop_tree		Forest	*Populus spp.*	T, b, si
C4grass		Grass	-	Tr g
C3grass	X	Grass	-	T g

Boreal (B), Temperate (T), Tropical (Tr), evergreen (e), broadleaved (b), needleleaved (n), grasses (g),
shade intolerant (si), shade tolerant (st), intermediate shade tolerant (ist)

Table 13. PFT present in Provence

7.5. Input data requirements for FARSITE v4.1.

Input parameter	Range & (metric) Units	File format	File extension	Requisite
Elevation	m	.ascii	.LCP	Required
Slope	degrees	.ascii	.LCP	Required
Aspect	1-25	.ascii	.LCP	Required
Fuel model	From 1 to 219	.ascii	.LCP	Required
Canopy cover	0-100 %	.ascii	.LCP	Required
Stand height	m (or m*10)	.ascii	.LCP	Optional
Crown base height	m (or m*10)	.ascii	.LCP	Optional
Crown bulk density	Kg/ m^3	.ascii	.LCP	Optional
Duff loading	T/ha	.ascii	.LCP	Optional
Coarse Woody	Coarse woody models	.ascii	.LCP	Optional
Adjustments	%	.txt	.ADJ	Required
Initial fuel moisture		.txt	.CNV	Required
Fuel model 1h	0-100%	.txt		Required
Fuel model 10h	0-100%	.txt		Required
Fuel model 100h	0-100%	.txt		Required
LiveH	0-100%	.txt		Required
LiveW	0-100%	.txt		Required
Custom Fuel Models		.txt	.FMD	Optional
Fuel model number	14-89	.txt		Optional
Fuel model code	up to 7 characters	.txt		Optional
Fuel loading 1h	T/ha	.txt		Optional

Fuel loading 10h	T/ha	.txt		Optional
Fuel loading 100h	T/ha	.txt		Optional
Fuel loading LiveH	T/ha	.txt		Optional
Fuel loading LiveW	T/ha	.txt		Optional
Fuel model type	"Static" or "dynamic"			Optional
Surface-to-volume ratio: Dead 1h	1/cm	.txt		Optional
Surface-to-volume ratio: LiveH	1/cm	.txt		Optional
Surface-to-volume ratio: LiveW	1/cm	.txt		Optional
Fuel bed depth	cm	.txt		Optional
Moisture of extinction	%	.txt		Optional
Heat content dead fuel	J/kg	.txt		Optional
Heat content live fuel	J/kg	.txt		Optional
Fuel model name	string	.txt		Optional
Coarse Woody		.txt	.CWD	Optional
Size class	cm	.txt		Optional
Loading	T/ha	.txt		Optional
Heat content	J/kg	.txt		Optional
Sound or rotten	mg/m3	.txt		Optional
Moisture	%	.txt		Optional
Weather		.txt	.WTR	Required
Month	1 to 12	.txt		Required
Day	1 to 31	.txt		Required

Daily precipitation	mm	.txt		Required
Hour of minimum temperature	0-2400 hr	txt		Required
Hour of maximum temperature	0-2400 hr	.txt		Required
Minimum temperature	°Celsius	.txt		Required
Maximum temperature	°Celsius	.txt		Required
Minimum humidity	0-99 %	.txt		Required
Maximum humidity	0-99 %	.txt		Required
Elevation	m	.txt		Required
Precipitation duration: rt1 & rt2	0-2400 hr	.txt		Optional
Wind		.txt	.WND	Required
Hour	0-2359 hr	.txt		Required
Speed (10 m)	0-300 km/h	.txt		Required
Direction	0-360°	.txt		Required
CloudCover	0-100 %	.txt		Required
Burn period		.txt	.CRW	Optional
Month	1 to 12	.txt		Optional
Day	1 to 31	.txt		Optional
StartHour	0-2400 hr	.txt		Optional
EndHour	0-2400 hr	.txt		Optional

Table 14. Input data requirements in FARSITE

7.6. Variable selection from LPJ-GUESS-SPITFIRE to FARSITE.

	Output parameter LPJ-GUESS	**Units**		**Input parameter FARSITE**	**Units**
Custom Fuel Model	fuel_1hr_total	gDM C/m^2	⟷	Fuel loading 1h	T/ha
	fuel_10hr_total	gDM C/m^2	⟷	Fuel loading 10h	T/ha
	fuel_100hr_total	gDM C/m^2	⟷	Fuel loading 100h	T/ha
	livegrass	gDM /m^2	⟷	Fuel loading LiveH	T/ha
	fuel_1000hr_total	g C/m^2	⟷	Fuel loading LiveW	T/ha
	lm	g/m^2	⟷		
	sm	g/m^2	⟷		
	hm	g/m^2	⟷		
	rm	g/m^2			
	sigma_1hr	66 cm^{-1}	⟷	SAV ratio: Dead 1h	1/cm
	sigma_10hr	3.58 cm^{-1}		SAV ratio: Dead 10h	1/cm
	sigma_100hr	0.98 cm^{-1}		SAV ratio: Dead 100h	1/cm
	sigma_grass	80 cm^{-1}	⟷	SAV ratio: LiveW	1/cm
	sigma_1000hr	0.5 cm^{-1}	⟷	SAV ratio: LiveH	1/cm

Custom Fuel Model	Litterme (grass)	0.2	⟵⟶	Moisture of extinction	%
	Litterme (shrub)	0.3	⟵⟶	Moisture of extinction	%
	Litterme (tree)	0.3	⟵⟶	Moisture of extinction	%
	H	18 000 KJ/Kg	⟵⟶	Heat content dead fuel	KJ/kg
	Fuel depth	m	⟵⟶	Fuel depth	m
Coarse woody model	steam diamer	cm	⟵⟶	Size class	cm
			⟵⟶	Loading	T/ha
			⟵⟶	Sound or rotten	mg/m^3
			⟵⟶	Moisture	%
Tree para-meters	fpc_tree	%	⟵⟶	Canopy cover	%
	height*crown_l	m	⟵⟶	Stand height	m
	crown_l	m	⟵⟶	Crown base height	m
			⟵⟶	Crown bulk density	Kg/ m^3
Fuel moisture	dlm_1		⟵⟶	Fuel model 1h	0-100%
	dlm_10		⟵⟶	Fuel model 10h	0-100%
	dlm_100		⟵⟶	Fuel model 100h	0-100%
	dlm_lg		⟵⟶	LiveH	0-100%
			⟵⟶	LiveW	0-100%

Table 15. Variable selection from LPJ-GUESS-SPITFIRE

7.7. LPJ-GUESS-SPITFIRE code’s implementation

1.

```
if (date.islastday && date.islastmonth) {
        // LAST DAY OF YEAR
                        // Call input/output module to output results for end of year
        // or end of simulation for this grid cell
            outannual(gridcell,pftlist);
                if(date.year>1000)
                {
                printf("year %d \n", date.year);
                }
        // Check whether to abort

        if (abort_request_received()) {
        termio();
        return 99;
        }
}
```

2.

```
    // crown_base_height: simple multiplication between tree height and crown length proportion
    fire_ind[indinummer].crown_base_height=(indiv.height)*(pftlist[indiv.pft.id].crown_l);
    // fuel_depth: dead load fuel (1h+10h+100h) divided by the fuel's density
    fuel_depth=dead_fuel/char_dens_fuel_ave;
```

```
// Following the same structure used by Thonicke et al. (2010)
for fuel moisture calculation (composite //estimate of moisture
content for 1h, 10h, 100h fuels), I decided to split the
calculation for each //specific fuel class: dlm_1hr, dlm_10hr,
dlm_100hr:

dlm_1hr=exp(-(alpha_1hr*fuel_1hr_total)*ni_acc[date.day]);
dlm_10hr=exp(-(alpha_10hr*fuel_10hr_total)*
ni_acc[date.day]);
dlm_100hr=exp(-(alpha_100hr*fuel_100hr_total)*
ni_acc[date.day]);

// Fire behaviour described by Andrews (1986)

flame_residence_time=12.595/sigma;
flame_length=0.047* pow (d_i_surface,0.46);
heat_per_unit_area=ir*flame_residence_time;
```

3.

```
        //Canopy cover

        printf("fpc grass %f % \n",fpc_grass_total);

        //Tree parameters (no individual calculation)

        printf("dbh %f cm \n",fire_ind->dbh,);
        printf("height %f m \n",fire_ind->height);
        printf("crown_base_height %f m \n",fire_ind-
>crown_base_height);
        printf("crown_l %f % \n",fire_ind->crown_length,);

        // Dead fuel loading

        printf("dead_fuel_sum %f gCDM/m2 \n",dead_fuel);
         // total fuel loading

        printf("fuel_1hr_total %f gCDM/m2 \n",fuel_1hr_total);// 1h
        printf("fuel_10hr_total %f gCDM/m2 \n",fuel_10hr_total);//
10h
        printf("fuel_100hr_total %f gCDM/m2
\n",fuel_100hr_total);// 100h
        printf("fuel_1000hr_total %f gCDM/m2
\n",fuel_1000hr_total);// 1000h
        printf("fuel_grass %f gC/m2 \n",livegrass);// living grass
```

```
        // Living fuel loading (Sum of individuals?)
        printf("leaf_mass %f g/m2 \n",fire_ind->lm);// Living leaf
mass
        printf("sapwood_mass %f g/m2 \n",fire_ind->sm);Living
sapwood mass
        printf("heartwood_mass %f \n",fire_ind->hm,"g/m2");Living
heartwood mass

        //Fuel depth
        printf("fuel_depth %f cm \n",fuel_depth);

        // Moisture-related
        printf("Mx %f \n",char_moistfactor);

        // Moisture of extinction
        printf("ni_acc %f \n",ni_acc[date.day]);// Nesterov Index
        printf("dlm_deadfuel %f \n",dlm);// Composite estimation
moisture
        printf("dlm_1h %f \n",dlm_1hr);// 1h fuel moisture
        printf("dlm_10h  %f \n",dlm_10hr);// 10h fuel moisture
        printf("dlm_100h  %f \n",dlm_100hr);// 100h fuel moisture
        printf("dlm_lg %f \n",dlm_lg);// living grass fuel moisture
```

4.

```
//Change loop's location allowing computation even during NO-FIRE
year's event. It is placed after calculation //of the variables

if (ifdespitefire &&
                                        has_not_burned_last_six_month
&&                                                          //only
perform calculation if patch has not already burned in the last six
months

                 (
                                                (fixrandfirereturninterval>-
0.5 && date.day==fixburnday-1) ||
        // if  fixrandfire is set only at the day when it burns

                        (fixfirereturninterval>-0.5 &&
                        date.day==fixburnday-1 && date.year %int
                        (fixfirereturninterval)==0.) ||
                                                // if  fixfire is
                        set only at the day when it burns
                                (readinburnarea &&
                        climate.fire_io.baprob>0) ||
                              // if burned area read is set, only to
```

```
                              do if the probability (ba) within the reading //
                              file is above 0
                                                  statisticburnarea ||
                                                                  ifdefafnd ||
                                                                   burnyear ==
                              date.year

                    )

            )

{

5.

//////////////FIRE BEHAVIOUR PFT SPECIFIC

for(int pft=0;pft<npft;pft++){
beta_pft[pft]=char_dens_fuel_ave_pft[pft]/part_dens;
beta_opt_pft[pft]=0.20395*(pow(sigma_pft[pft],-0.8189)); //FIX
//beta_opt_pft[pft]=0.200395*(pow(sigma_pft[pft],-0.8189));
bet_pft[pft]=beta_pft[pft]/beta_opt_pft[pft];
/////////////////////////////////////////////////heat of pre ignition
q_ig_pft[pft]=581+2594*dlm_pft[pft];  // FIX
//q_ig_pft[pft]=581+94*dlm_pft[pft];
/////////////////////////////////////////////////effective heating number
eps_pft[pft]=exp(-4.528/sigma_pft[pft]);
/////////////////////////////////////////////////influence of wind speed
a_pft[pft]=8.9033*pow(sigma_pft[pft],-0.7913);
//b_pft[pft]=0.15988*pow(sigma_pft[pft],0.55);           //FIX
b_pft[pft]=0.15988*pow(sigma_pft[pft],0.54);
c_pft[pft]=7.47*(exp(-0.8711*pow(sigma_pft[pft],0.55)));
e_pft[pft]=0.715*(exp(-0.01094*sigma_pft[pft]));
phi_wind_pft[pft]=c_pft[pft]*(pow(wind_forward_pft[pft],b_pft[pft])
)*pow(bet_pft[pft],-e_pft[pft]); // was base_wind before
/////////////////////////////////////////////////////////////propagating
flux                M_16
if (sigma_pft[pft]<0.00001)
xi_pft[pft]=0.;
else
{
xi_pft[pft]=(exp((0.792+3.7597*pow(sigma_pft[pft],0.5))*(beta_pf
t[pft]+0.1)))/(192+7.9095*sigma_pft[pft]);
}
/////////////////////////////////////////////////////////////reaction
intensity                M_17
if (sigma_pft[pft]<=0.00001)
```

```
dummy_pft[pft]=0.;
else
dummy_pft[pft]=exp(a_pft[pft]*(1-bet_pft[pft]));
gamma_max_pft[pft]=1/(0.0591+2.926*pow(sigma_pft[pft],-1.5));
gamma_aptr_pft[pft]=gamma_max_pft[pft]*pow(bet_pft[pft],a_pft[pft])*dummy_pft[pft];
if (char_moistfactor_pft[pft]>0.)
mw_weight_pft[pft]=dlm_pft[pft]/char_moistfactor_pft[pft];
else
mw_weight_pft[pft]=0.;
moist_damp_pft[pft]=max(0.,(1-(2.59*mw_weight_pft[pft])+(5.11*(mw_weight_pft[pft]*mw_weight_pft[pft]))-(3.52*pow(mw_weight_pft[pft],3))));
ir_pft[pft]=gamma_aptr_pft[pft]*char_net_fuel_pft[pft]*H*moist_damp_pft[pft]*MINER_DAMP;
if (((char_dens_fuel_ave_pft[pft]<=0.) | (eps_pft[pft]<=0.) | (q_ig_pft[pft]<=0.) |(ir_pft[pft]<=0. )))
u_front_pft[pft]=0.;
else
u_front_pft[pft]=(ir_pft[pft]*xi_pft[pft]*(1.0+phi_wind_pft[pft]))/(char_dens_fuel_ave_pft[pft]*eps_pft[pft]*q_ig_pft[pft]); // ROS
ros_f_pft[pft]=u_front_pft[pft];
////////////////////////////////////////////////////////////////////Backward spread
ros_b_pft[pft]=ros_f_pft[pft]*exp(-0.012*wind_speed_pft[pft]);
////////////////////////////////////////////////////////////////////fire duration                M_19
if (ros_b_pft[pft]<0.05 ) //0.05
ros_b_pft[pft]=0.;

fire_durat_pft[pft]=241/(1+(((240))*exp(-11.06*d_fdi_pft[pft])));
db_pft[pft]=ros_b_pft[pft]*fire_durat_pft[pft];
df_pft[pft]=ros_f_pft[pft]*fire_durat_pft[pft]; //}
if (net_fuel_pft[pft]<=0.) {
                    ros_b_pft[pft]=0.;
                    db_pft[pft]=0.;
                    ros_f_pft[pft]=0.;
                    df_pft[pft]=0.;
          }
if (date.year==1025 && date.day==212)
{
printf(" pft %d year %d date %d ROS %f ROStot %f Ir %f Irtot %f \n", pft,date.year,date.day,ros_f_pft[pft],ros_f,ir_pft[pft],ir);
}
```

6.

```
//////////////////////////////////////////////////////////////////////////////
//// // Fire DYNAMICS(fire.cpp)
// Should be called from vegetation dynamics only instead of using
the old Fire routine                    // Measurement of fuel-related
parameters (1) and fire behaviour parameters (2)
/////////////////////////////////////////(1)/////////////////////////////////
//////

if (date.year>999 && date.day>=211 && date.day<=213)

        {

         FILE * pFile;

         pFile = fopen ("fire_out.txt","a");

         if (pFile!=NULL)

         {

        fprintf(pFile,"%d %d %d %f %f %f %f %f %f %f %f %f %f
        %f     %f     %f     %f     %f     %f     \n"     ,patch.id,
        date.year,date.day,fpc_tree_total*100,fpc_grass_total*100,de
        ad_fuel*0.001,fuel_1hr_total*0.001,fuel_10hr_total*0.001,fue
        l_100hr_total*0.001,fuel_1000hr_total*0.001,livegrass*0.001
        ,fuel_depth*0.1,char_moistfactor*100,ni_acc[date.day],dlm*1
        00,dlm_1hr*100,dlm_10hr*100,dlm_100hr*100,lm_lg*100);

        fclose (pFile);

        }

}

////////////////////////////////////////(2)///////////////////////////////////
//////

if (date.year>999 )

        {

         FILE * pFile;

          pFile = fopen ("fire_behaviour_out.txt","a");

         if (pFile!=NULL)

        {                                               fprintf(pFile,"%d
```

```
        %d %d %f %f %f %f %f %f %f %f %f %f %f %f %f  %f %f
        %f %f %f %f %f \n" ,patch.id,
        date.year,date.day,ir,xi,phi_wind,beta,eps,q_ig,ROS_f,ROS_b,
        bet,
        beta_opt,fire_durat,db,df,d,numfire,d_fdi,fire_frac,area,flame_
        residence_time,flame_length,heat_per_area);

        fclose (pFile);

        }

}

////////////////////////////////////////////////////////////////////////////
//////TREE ALLOMETRY (growth.cpp)
//Should be called to update allometry, FPC and FPC increment
whenever biomass values for a vegetation //individual change.
Calculates tree allometry (height and crown area) and fractional
projective given carbon //biomass in various compartments for an
individual.
////////////////////////////////////////////////////////////////////////////
/////////

if (date.year>999)

        {

        FILE * pFile;

        pFile = fopen ("tree_out.txt","a");

         if (pFile!=NULL)

         {

        fprintf(pFile, "%d %d %d %d %f %f %f %f %f %f  \n"
        ,nr_of_patch,date.year,date.month, date.day,indiv.height,
        indiv.pft.crown_l,indiv.cmass_leaf,
        ,indiv.cmass_sap,indiv.cmass_heart, vol );

        fclose (pFile);

        }

}
```

7.8. LPJ-GUESS-SPITFIRE code's modification

1.

```
//Start of calculations based on Rothermel's equations
beta=char_dens_fuel_ave/part_dens;
beta_opt=0.20395*(pow(sigma,-0.8189)); // Instead of
beta_opt=0.200395*(pow(sigma,-0.8189));
bet=beta/beta_opt;
/////////////////////////////////////////////////heat of pre ignition
q_ig=581+2594*dlm;  // Instead of q_ig=581+94*dlm
```

2.

```
// Area calculation  in m2
area=(12321200000*cos(climate.lat*0.017453280))*pixeldegree*pixeldegree;
// instead of
area=(1232120000*cos(climate.lat*0.017453280))*pixeldegree*pixeldegree
```

7.9. Synthetic landscape's creation from LPJ-GUESS-SPITFIRE through MATLAB code

```
%%% Importation from .txt file computed in LPJ-GUESS-SPITFIRE.
Canopy cover, tree height, crown height and fuel follow the same
structure. An example of CC is shown%%%

clear, clf
format short

% Importing output data from LPJ-GUESS-SPITFIRE
load CC.txt

% Creating 1000000 m2 synthetic landscape ((10x10)*100)
!patch(1:100)=1:100;
mapmatrix= zeros(100,10);
for patchi=1:100,
    for cellxi=1:10,
        for cellyi=1:10,
            mapmatrix(mod(patchi-
1,10)*10+cellxi,ceil(patchi/10)*10+cellyi)=CC(patchi);
            ,end,end,end;



xlswrite('CC.xls',mapmatrix)

% Creating 10000 m2 synthetic landscape (10x10)
mapmatrix1= zeros(10,10);
for i=1:10;
    for j=1:10;
        mapmatrix1(i,j)= mapmatrix(i+(i-1)*10,j*10+1);
    end
end

imagesc(mapmatrix1);

xlswrite('CC1.xls',mapmatrix1)
```

7.10. Fuel-related variables in a 30 years' time series

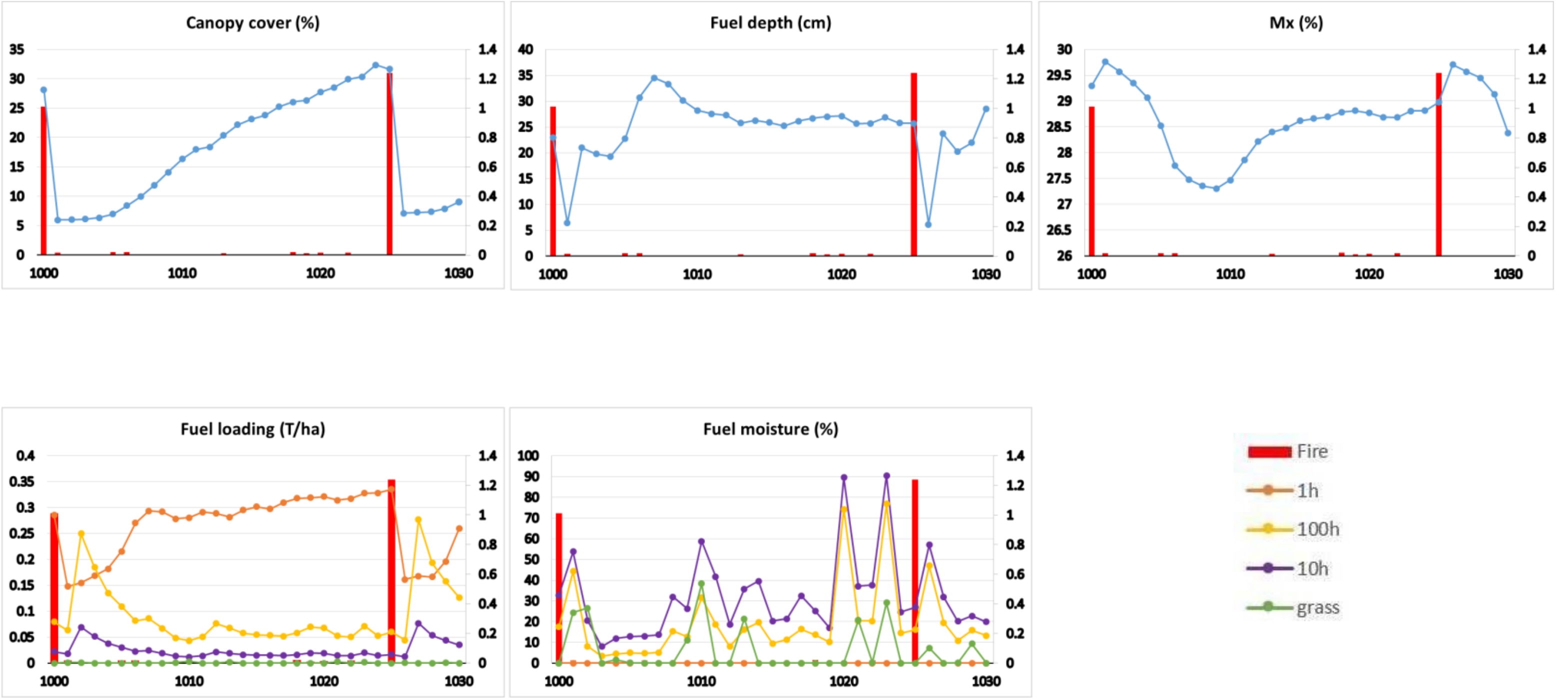


Figure 22. Canopy cover, fuel depth, Mx, fuel loading and fuel moisture mean values over 30 years' time series

7.11. Synthetic landscape based on 9 patch custom fuel model

Fuel Model	Fuel load (t.ha^{-1})				Depth (cm)	Mx (%)	Initial DFMC (%)			LFMC (%)	
	1h	10h	100h	live			1h	10h	100h	H	W
p14	3.08	1.01	3.63	2.57	77.13	30	2	2	2	5.00	100.00
p15	2.34	0.01	0.03	2.57	23.79	29.45	2	75.71	40.84	5.00	100.00
p16	2.18	0.03	0.09	2.57	22.93	29.96	2	39.33	4.96	5.00	100.00
p24	2.77	0	0	2.57	27.68	28.19	2	99.99	99.96	5.00	100.00
p25	2.47	1.04	3.74	2.57	72.44	29.99	2	2	2	5.00	100.00
p26	2.8	1.17	4.2	2.57	81.64	29.92	2	2	2	5.00	100.00
p34	3.08	0.04	0.13	2.57	32.52	29.79	2	26.32	2	5.00	100.00
p35	3.35	0.9	3.23	2.57	74.71	29.58	2	2	2	5.00	100.00
p36	2.92	0	0	2.57	29.24	29.71	2	99.96	99.87	5.00	100.00

* Heat content=18600 kJ/Kg for all fuel models

Table 16. Custom fuel model of 9 patches

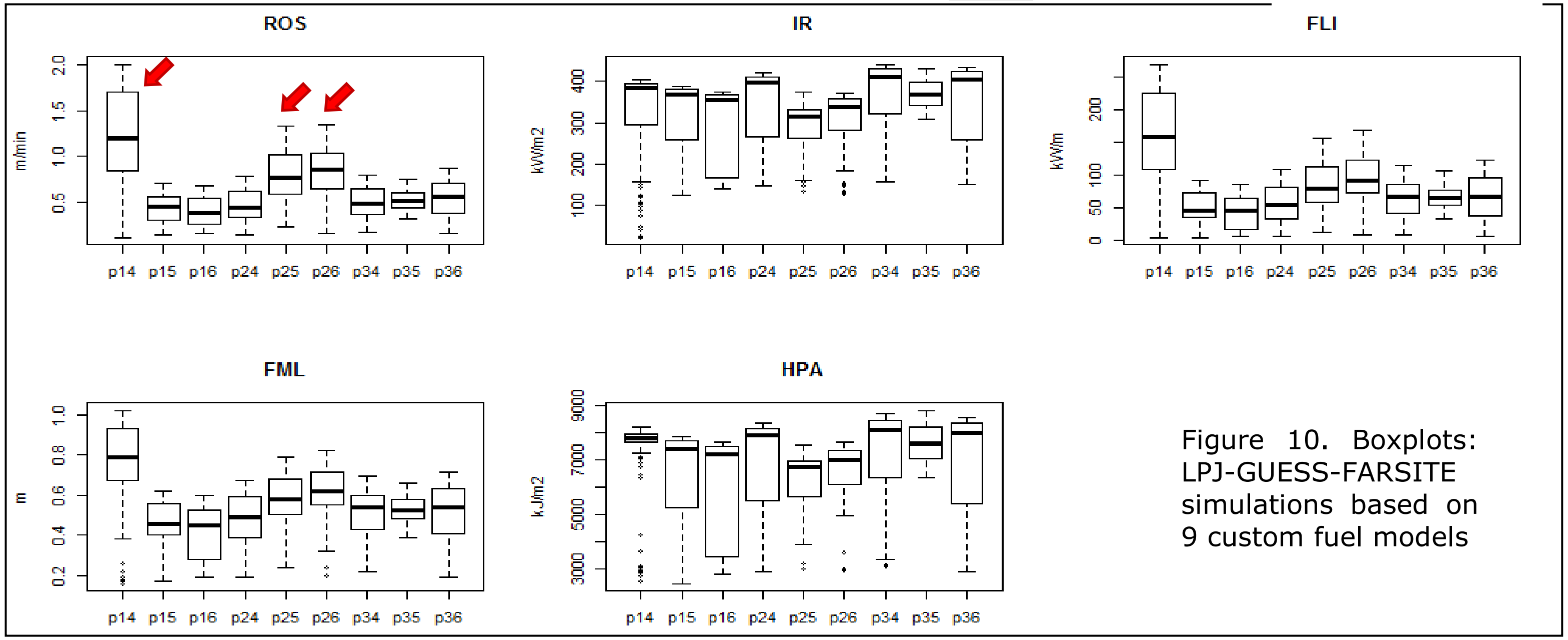


Figure 10. Boxplots: LPJ-GUESS-FARSITE simulations based on 9 custom fuel models

7.12. Observed vs simulated ROS measurements in Sardinia, Italy (Salis 2007).

					Conditions					**ROS**	
	Date	**Plant height (m)**	**Dominate Spp**	**Max temp (°C)**	**Min temp (°C)**	**Mean temp**	**Relative humidity (%)**	**Wind speed (km/h)**	**Wind direction (°)**	**Observed (m/min)**	**Simulated (m/min)**
Location A	August 26, 2004	1.0-4.0	*Pistacia lentiscus L. Olea europaca L. var. oleaster, Cistus monpeliensisL., Myrtus communis L.*	28	20	-	-	35	western-south-western	8.1	8.1
Location B	August 21, 2004	-	*Pistacia lentiscus L., Arbutus Unedo L., Olea europaca L. var. oleaster, Cistus spp., Myrtus communis L.*	-	-	24	35	15	280	2.8	3
Location C	August 11, 2004	1.5-2.0	*Pistacia lentiscus L., Arbutus Unedo L., Olea europaca L. var. oleaster, Cistus spp., Myrtus communis L.*	39	25	-	-	13	295	13	13
Location D	July 15, 2006	1.0-1.5	*Pistacia lentiscus L., Arbutus Unedo L., Myrtus communis L, grass*	36	20	-	-	11	40	4.6	4.6

Table 17. Observed vs Simulated ROS

7.13. Examples of fire behaviour. From Albini F.A unpublished training notes (Pyne et al. (1996)

ROS (m/min)	Typical fire situation	Equivalent to
0.31	Litter fire, no wind no slope	Line building rate for one person in heavy fuel
7.62	Aged medium slash, 100% slope	Backpacker going up 100% slope
76.2	Low sagebrush, Santa Ana wind	Brisk walk on level ground
243.8	Chaparral, Santa Ana wind	Good pace for a marathon run
365,8	Dry, short grass, strong wind	4-minute mile

Table 18. Examples of Rate of Spread

IR (kW/m2)	Fuel consumed (T/ha)	Energy released on 0.61 m2 would…
56.78	1.9 (grass)	Warm up 2 quarts of stew
227.11	7.4 (tall grass)	Boil away 1 pint of water
757.06	24.7 (2.5 cm. pine duff)	Open car thermostat
2271.18	74.1 (thinning slash)	Heat 10 Pulaski heads to full cherry red
9084.74	296.5(heavy logging debris)	Melt down an aluminium engine block (52 kg)

Table 19. Examples of Reaction intensity

FML (m)	FLI (Kj/m/s)	Fire suppression interpretation
< 1.2	**<346.1**	Fire can generally be attacked at the head or flanks
1,2 – 2.4	**346.1-1730.6**	Fires are too intense for direct attack on the head
2.4- 3.4	**1730.6-3461.3**	Fires may present serious control problems: torching, crowing and spotting. Control efforts at fire head will probably be ineffective
>3.4	**>3461.3**	Crowing and spotting and major fire runs are probable. Control efforts at fire head are ineffective

Table 20. Flame length and Fire-line intensity related to fire suppression activities

7.14. Scripts used in digital format.

Due to the large extension of each of the implementations, and the new routine created along the original code, a full copy of the modified code has been enclosed in digital format instead. The CD enclosed to the MSc thesis includes 3 folders containing:

1. LPJ-GUESS-SPITFIRE:

   -Folder "eclipse_proj_fire": the guess_ins.txt and gridlist.txt used.

   -Folder "fire" and sub-folder "modules": the altered versions of the codes. Major changes are presented in fire.cpp and growth.cpp module.

2. R:

   -All the scripts involving the visualization of histograms and boxplots together with the statistical tests performed are in COMPARISON ANALYSIS.R.

   -Row data used for each theme.

3. MATLAB:

   -The script in charge of the synthetic landscape generation is written in Metamodel_m.

   -Row data (Canopy cover, tree height, crown height and fuel) for each map creation.

8. List of references

Acácio, V., M. Holmgren, F. Rego, F. Moreira, and G. M. J. Mohren. 2009. Are drought and wildfires turning Mediterranean cork oak forests into persistent shrublands? *Agroforestry Systems,* 76**:** 389-400. DOI: 10.1007/s10457-008-9165-y

Albini, F. A., 1976a. Estimating Wildfire Behaviour and Effects. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-30, Ogden, Utah, USDA Forest Service 100 pp.

Albini, F. A., 1979. Spot Fire Distance from Burning Trees: A Predictive Model. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-56, Ogden, Utah, USDA Forest Service 80 pp.

Albini, F. A., and E. D. Reinhardt. 1995. Modeling ignition and burning rate of large woody natural fuels. *International Journal of Wildland Fire,* 5(2)**:** 81-91.

Alexander, M. E., and M. G. Cruz. 2012. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *International Journal of Wildland Fire,* 21**:** 95-113. DOI: http://dx.doi.org/10.1071/WF11001

Anderson, D. H., E. A. Catchpole, N. J. De Mestre, and T. Parkes. 1982. Modelling the spread of grass fires. *The ANZIAM Journal,* 23**:** 451-466. DOI: doi:10.1017/S0334270000000394

Anderson, H. E., 1969. Heat Transfer and Fire Spread. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture Research Paper INT-69, Ogden, Utah, USDA Forest Service 29 pp.

Anderson, H. E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-122, Ogden, Utah, USDA Forest Service 28 pp.

Andrews, P. L., 1986. BEHAVE: Fire Behavior Prediction and Fuel Modeling System - BURN Subsystem, Part 1. Intermountain Forest and Range Experiment Station, Forest Service, U.S.

Department of Agriculture General Technical Report INT-194, Ogden, Utah, USDA Forest Service 134 pp.

Arca, B., P. Duce, M. Laconi, G. Pellizzaro, M. Salis, and D. Spano. 2007. Evaluation of FARSITE simulator in Mediterranean maquis. *International Journal of Wildland Fire,* 16**:** 563-572. DOI: http://dx.doi.org/10.1071/WF06070

Arca, B., M. Laconi, A. Maccioni, G. Pellizzaro, and M. Salis. 2005. Validation of Farsite Model in Mediterranean Area. 4. University of Sassari.

Archibald, S., A. Nickless, N. Govender, R. J. Scholes, and V. Lehsten. 2010. Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data. *Global Ecology and Biogeography,* 19**:** 794-809. DOI: 10.1111/j.1466-8238.2010.00568.x

Arora, V. K., and G. J. Boer. 2005. Fire as an interactive component of dynamic vegetation models. *Journal of Geophysical Research-Biogeosciences,* 110. DOI: 10.1029/2005jg000042

Barrows, J. S., 1951. Fire Behavior in Northern Rocky Mountain Forests. Northern Rooky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture Station Paper No. 29, Missoua, Montana, USDA Forest Service 134 pp.

Bowman, D., J. K. Balch, P. Artaxo, W. J. Bond, J. M. Carlson, M. A. Cochrane, C. M. D'Antonio, R. S. DeFries, et al. 2009. Fire in the Earth System. *Science,* 324**:** 481-484. DOI: 10.1126/science.1163886

Byram, G. M. 1959. Combustion of Forest Fuels. In*: Davis, K. P. Forest Fire: Control and Use*, 61-89 pp. New York: McGraw-Hill Book Company.

Canellas, I., and A. S. Miguel. 1998. Litter fall and nutrient turnover in Kermes oak (Quercus coccifera L.) shrublands in Valencia (eastern Spain). *Annales Des Sciences Forestieres,* 55**:** 589-597. DOI: 10.1051/forest:19980506

Caritat, A., E. García-Berthou, R. Lapeña, and L. Vilar. 2006. Litter production in a Quercus suber forest of Montseny (NE Spain) and its relationship to meteorological conditions. *Ann. For. Sci.,* 63**:** 791-800. DOI: http://dx.doi.org/10.1051/forest:2006061

Castells, E., J. Peñuelas, and D. W. Valentine. 2004. Are phenolic compounds released from the Mediterranean shrub Cistus albidus responsible for changes in N cycling in siliceous and calcareous soils? *New Phytologist,* 162**:** 187-195. DOI: 10.1111/j.1469-8137.2004.01021.x

Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams. 1983. *Fire in forestry. Volume 1. Forest fire behavior and effects*. New York: John Wiley & Sons, Inc.

Cheney, N. P., and J. S. Gould. 1995. Fire Growth in Grassland Fuels. *International Journal of Wildland Fire,* 5**:** 237-247. DOI: http://dx.doi.org/10.1071/WF9950237

Cohen, J. D., and J. E. Deeming, 1985. The National Fire-Danger Rating System: basic equations. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report PSW-82, Berkeley, California, USDA Forest Service, 23 pp.

Cramer, W., A. Bondeau, F. I. Woodward, I. C. Prentice, R. A. Betts, V. Brovkin, P. M. Cox, V. Fisher, et al. 2001. Global response of terrestrial ecosystem structure and function to CO2 and climate change: results from six dynamic global vegetation models. *Global Change Biology,* 7**:** 357-373. DOI: 10.1046/j.1365-2486.2001.00383.x

Curt, T., W. Adra, and L. Borgniet. 2009. Fire-driven oak regeneration in French Mediterranean ecosystems. *Forest Ecology and Management,* 258**:** 2127-2135. DOI: 10.1016/j.foreco.2009.08.010

Curt, T., L. Borgniet, and C. Bouillon. 2013. Wildfire frequency varies with the size and shape of fuel types in southeastern France: Implications for environmental management. *Journal of Environmental Management,* 117**:** 150-161. DOI: 10.1016/j.jenvman.2012.12.006

Curt, T., A. Schaffhauser, L. Borgniet, C. Dumas, R. Esteve, A. Ganteaume, M. Jappiot, W. Martin, et al. 2011. Litter flammability in oak woodlands and shrublands of southeastern France. *Forest Ecology and Management,* 261**:** 2214-2222. DOI: 10.1016/j.foreco.2010.12.002

Curt, T., A. Schaffhauser, L. Borgniet, R. Esteve, A. Ganteaume, M. Jappiot, C. Lampin-Maillet, W. Martin, et al. 2010. Litter flammability of French Mediterranean vegetation types: a cross-substratum analysis. In *VI International Conference on Forest Fire Research* ed. D. X. Viegas, 8. Coimbra, Portugal.

Delitti, W., A. Ferran, L. Trabaud, and V. R. Vallejo. 2005. Effects of fire recurrence in Quercus coccifera L. shrublands of the

Valencia Region (Spain): I. plant composition and productivity. *Plant Ecology,* 177**:** 57-70. DOI: 10.1007/s11258-005-2140-z

Dopheide, E., F. van der Meer, R. Sliuzas, A. van der Veen, and A. Voinov. 2012. System Earth: some theory on the system. In *The core of GIScience: a systems-based approach*. Enschede, The Netherlands: The International Institute for Geo-Information Science and Earth Observation (ITC).

Eugenio, M., I. Verkaik, F. Lloret, and J. M. Espelta. 2006. Recruitment and growth decline in Pinus halepensis populations after recurrent wildfires in Catalonia (NE Iberian Peninsula). *Forest Ecology and Management,* 231**:** 47-54. DOI: http://dx.doi.org/10.1016/j.foreco.2006.05.007

FCFDG, 1992. Development and Structure of the Canadian Forest Fire Behavior Prediction System. Group Information Report ST-X-3, Ottawa,Forestry Canada Fire Danger

Finney, M. A., 2004. FARSITE: Fire Area Simulator - Model development and evaluation. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture. Rearch Paper RMRS-RP-4 (Revised), Fort Collins, CO, USDA Forest Service 52 pp.

Finney, M. A., R. C. Seli, and P. L. Andrews. 2003. Modeling post-frontal combustion in the FARSITE fire area simulator. In *Second International Wildland Fire Ecology and Fire Management Congress and Fifth Symposium on Fire and Forest Meteorology*, p. 125. Orlando, FL. : American Meteorological Society.

Foley, J. A. 1995. An equilibrium model of the terrestrial carbon budget. *Tellus B,* 47**:** 310-319. DOI: 10.1034/j.1600-0889.47.issue3.3.x

Fosberg, M. A., W. Cramer, V. Brovkin, R. Fleming, R. Gardner, A. M. Gill, J. G. Goldammer, R. Keane, et al. 1999. Strategy for a fire module in dynamic global vegetation models. *International Journal of Wildland Fire,* 9**:** 79-84. DOI: 10.1071/wf99007

Frandsen, W. H. 1971. Fire spread through porous fuels from the conservation of energy. *Combustion and Flame,* 16**:** 9-16. DOI: 10.1016/S0010-2180(71)80005-6

Fujioka, F. M., A. M. Gill, D. X. Viegas, and B. M. Wotton. 2008. Fire Danger and Fire Behavior Modeling Systems in Australia, Europe, and North America. In *Wildland Fires and Air Pollution. Developments in Environmental Science,* eds. Andrzej Bytnerowicz, M. J. Arbaugh, A. R. Riebau, and A. Christian, 471-497 pp.: Elsevier.

Ganteaume, A., M. Jappiot, C. Lampin-Maillet, T. Curt, and L. Borgniet. 2009. Fuel characterization and effects of wildfire recurrence on vegetation structure on limestone soils in southeastern France. *Forest Ecology and Management,* 258**:** S15-S23. DOI: 10.1016/j.foreco.2009.07.021

Ganteaume, A., M. Jappiot, C. Lampin-Maillet, T. Curt, and L. Borgniet. 2011. Effects of vegetation type and fire regime on flammability of undisturbed litter in Southeastern France. *Forest Ecology and Management,* 261**:** 2223-2231. DOI: http://dx.doi.org/10.1016/j.foreco.2010.09.046

Gill, A. M. 1979. Fire in the Australian landscape. *Landscape Planning,* 6**:** 343-357. DOI: http://dx.doi.org/10.1016/0304-3924(79)90037-6

Gordon, B. B. 2008. *Ecological Climatology: Concepts and Applications (2nd Edition)*. New York: Cambridge University Press.

Hättenschwiler, S., and P. M. Vitousek. 2000. The role of polyphenols in terrestrial ecosystem nutrient cycling. *Trends in Ecology & Evolution,* 15**:** 238-243. DOI: http://dx.doi.org/10.1016/S0169-5347(00)01861-9

Houghton, J. T., Y. Ding, D. J. Griggs, N. Noguer, P. J. Van der Linden, D. Xiaosu, K. Maskell, and C. A. Johnson, 2001. Climate change 2001: The scientific basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panle on Climate Change. Candbridge University Press 1477-870X, New York.

Incerti, G., G. Bonanomi, F. Giannino, F. A. Rutigliano, D. Piermatteo, S. Castaldi, A. De Marco, A. Fierro, et al. 2011. Litter decomposition in Mediterranean ecosystems: Modelling the controlling role of climatic conditions and litter quality. *Applied Soil Ecology,* 49**:** 148-157. DOI: http://dx.doi.org/10.1016/j.apsoil.2011.06.004

Johnson, E. A., and K. Miyanishi. 2001. *Forest Fires: Behavior and Ecological Effects*. Elsevier Science.

JRC-EFFIS. 2012. Forest Fires in Europe, Middle East and North Africa. 118p. Land Management and Natural Hazards Unit.

Lehsten, V. 2013. Vegetation Dynamics: Determinants of global vegetation and atmospheric interaction, lecture notes, Greenhouse Gases and the Carbon Cycle NGEN04 Lund University, delivered 4th October 2013.

Lehsten, V., P. Harmand, I. Palumbo, and A. Arneth. 2010. Modelling burned area in Africa. *Biogeosciences,* 7**:** 3199-3214. DOI: 10.5194/bg-7-3199-2010

Lehsten, V., K. Tansey, H. Balzter, K. Thonicke, A. Spessa, U. Weber, B. Smith, and A. Arneth. 2009. Estimating carbon emissions from African wildfires. *Biogeosciences,* 6**:** 349-360.

Lenihan, J. M., C. Daly, D. Bachelet, and R. P. Neilson. 1998. Simulating broad-scale fire severity in a Dynamic Global Vegetation Model. *Northwest Sci.,* 72**:** 91-103. DOI: citeulike-article-id:11388074

Li, F., X. D. Zeng, and S. Levis. 2012. A process-based fire parameterization of intermediate complexity in a Dynamic Global Vegetation Model. *Biogeosciences,* 9**:** 2761-2780. DOI: 10.5194/bg-9-2761-2012

Malamud, B. D., and D. L. Turcotte. 1999. Self-Organized Criticality Applied to Natural Hazards. *Natural Hazards,* 20**:** 93-116. DOI: 10.1023/A:1008014000515

McAlpine, R. S., and R. H. Wakimoto. 1991. The Acceleration of Fire from Point-source to Equilibrium Spread. *Forest Science,* 37**:** 1314-1337.

Missoula Fire Science Laboratory. 2010. Dead Fuel Moisture (technical documentation). Retrieved 14 February 2014, from http://www.fire.org/downloads/farsite/WebHelp/technicalreferences/tech_dead_fuel_moisture.htm.

Morandini, F., X. Silvani, L. Rossi, P. Santoni, A. Simeoni, J. H. Balbi, J. Louis Rossi, and T. Marcelli. 2006. Fire spread experiment across Mediterranean shrub: Influence of wind on flame front properties. *Fire Safety Journal,* 41**:** 229-235. DOI: http://dx.doi.org/10.1016/j.firesaf.2006.01.006

Morandini, F., A. Simeoni, P. A. Santoni, J. H. Balbi, F. Morandini, A. Simeoni, P. A. Santoni, and J. H. Balbi. 2005. A model for the spread of fire across a fuel bed incorporating the effects of wind and slope. *Combustion Science and Technology,* 177**:** 1381-1418. DOI: 10.1080/00102200590950520

Moreira, F., O. Viedma, M. Arianoutsou, T. Curt, N. Koutsias, E. Rigolot, A. Barbati, P. Corona, et al. 2011. Landscape - wildfire interactions in southern Europe: Implications for landscape management. *Journal of Environmental Management,* 92**:** 2389-2402. DOI: 10.1016/j.jenvman.2011.06.028

Nesterov, V. G. 1949. *Combustibility of the Forest and Methods for its Determination* [in Russian]. USSR State Industry Press.

Olson, J. 1963. Energy Storage and the Balance of Producers and Decomposers in Ecological Systems. *Ecology,* 44**:** 322-331. DOI: 10.2307/1932179

Pausas, J. G. 1997. Resprouting of Quercus suber in NE Spain after fire. *Journal of Vegetation Science,* 8**:** 703-706. DOI: 10.2307/3237375

Pausas, J. G. 1999. Mediterranean vegetation dynamics: modelling problems and functional types. *Plant Ecology,* 140**:** 27-39. DOI: 10.1023/A:1009752403216

Paysen, T. E., R. J. Ansley, J. K. Brown, G. J. Gottfried, S. M. Haase, M. G. Harrington, M. G. Narog, S. S. Sackett, et al. 2000. Fire in western shrubland, woodland, and grassland ecosystems. In *Wildland fire in ecosystems: effects of fire on flora,* eds. B. J. K., and S. J. K., 121-159 pp. Ogden, Utah, USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42-vol. 2.

Persson, Y. 2013. Refining fuel loads in LPJ-GUESS-SPITFIRE for wet-dry areas-with an emphasis on Kruger National Park in South Africa. MSc Thesis. Lund: University of Lund

Pfeiffer, M., and J. O. Kaplan. 2012. SPITFIRE-2: an improved fire module for Dynamic Global Vegetation Models. *Geoscientific Model Development Discussions,* 5. DOI: 10.5194/gmdd-5-2347-2012

Plucinski, M. P., and W. R. Anderson. 2008. Laboratory determination of factors influencing successful point ignition in the litter layer of shrubland vegetation. *International Journal of Wildland Fire,* 17**:** 628-637.

Prentice, I. C., A. Bondeau, W. Cramer, S. P. Harrison, T. Hickler, W. Lucht, S. Sitch, B. Smith, et al. 2007. Dynamic Global Vegetation Modeling: Quantifying Terrestrial Ecosystem Responses to Large-Scale Environmental Change. In *Terrestrial Ecosystems in a Changing World,* eds. J. Canadell, D. Pataki, and L. Pitelka, 175-192 pp. Berlin Heidelberg: Springer

Prentice, I. C., G. D. Farquhar, M. J. R. Fasham, M. L. Goulden, M. Heimann, V. J. Jaramillo, H. S. Kheshgi, C. Le Quéré, et al. 2001. The carbon cycle and atmospheric carbon dioxide, in Climate Change 2001: The Scientific Basis. In *Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* eds. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, 183–237 pp. Cambridge, United Kingdom and New York, USA: Cambridge University Press.

Prentice, I. C., D. I. Kelley, P. N. Foster, P. Friedlingstein, S. P. Harrison, and P. J. Bartlein. 2011. Modeling fire and the terrestrial carbon balance. *Global Biogeochemical Cycles,* 25. DOI: 10.1029/2010gb003906

Pyne, S. J., P. L. Andrews, and R. D. Laven. 1996. *Introduction to wildland fire*. New York: John Wiley & Sons, Inc.

Quézel, P., and F. Médail. 2003. *Ecology and Biogeography from Forest in Mediterranean basins* [in French]. Paris: Elsevier.

Quinn, G. P., and J. M. Keough. 2002. *Experimental design and data analysis for biologists*. United States of America: Cambridge University Press.

R Development Core Team. 2005. R: A Language and Environment for Statistical Computing, Reference Index Version v. 2.5.1. R Foundation for Statistical Computing, Vienna, Austria.

Rapp, M., and P. Lossaint. 1981. Some aspects of mineral cycling in the garrigue of southern France. In *Mediterranean-Type Shrublands. Origin and Structure,* eds. F. di Castri, D. W. Goodall, and R. L. Specht, 289- 301 pp. Amsterdam: Elsevier Scientific Publishing Company.

Rothermel, R. C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-115, Ogden, Utah, USDA Forest Service 48 pp.

Rothermel, R. C., 1983. How to Predict the Spread and Intensity of Forest and Range Fires. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-143, Ogden, Utah, USDA Forest Service 161 pp.

Rothermel, R. C., 1991. Predicting Behavior and Size of Crown Fires in the Northern Rocky Mountains. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-438, Ogden, Utah, USDA Forest Service 46 pp.

Salis, M. 2007. Fire behaviour simulation in mediterranean maquis using FARSITE (Fire Area Simulator). PhD Thesis University of Sassari

Santoni, P. A., A. Simeoni, J. L. Rossi, F. Bosseur, F. Morandini, X. Silvani, J. H. Balbi, D. Cancellieri, et al. 2006. Instrumentation of wildland fire: Characterisation of a fire spreading through a Mediterranean shrub. *Fire Safety Journal,* 41**:** 171-184. DOI: http://dx.doi.org/10.1016/j.firesaf.2005.11.010

Schaffhauser, A., T. Curt, and T. Tatoni. 2011. Fire-vegetation interplay in a mosaic structure of Quercus suber woodlands and Mediterranean maquis under recurrent fires. *Forest Ecology and Management,* 262**:** 730-738. DOI: 10.1016/j.foreco.2011.05.003

Schaffhauser, A., T. Curt, E. Vela, and T. Tatoni. 2012a. Fire recurrence effects on the abundance of plants grouped by traits in Quercus suber L. woodlands and maquis. *Forest Ecology and Management,* 282**:** 157-166. DOI: 10.1016/j.foreco.2012.06.047

Schaffhauser, A., T. Curt, E. Vela, and T. Tatoni. 2012b. Recurrent fires and environment shape the vegetation in Quercus suber L. woodlands and maquis. *Comptes Rendus Biologies,* 335**:** 424-434. DOI: 10.1016/j.crvi.2012.04.006

Schlesinger, W. H., and E. S. Bernhardt. 2013. The Biosphere: The Carbon Cycle of Terrestrial Ecosystems. In *Biogeochemistry (Third Edition),* eds. W. H. Schlesinger, and E. S. Bernhardt, 135-172 pp. Boston: Academic Press.

Scott, J. H., and R. E. Burgan, 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture General Technical Report RMRS-GTR-153, Fort Collins, CO, USDA Forest Service 80 pp.

Scott, J. H., and E. D. Reinhardt, 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. Rocky Mountain Research Station, Forest Service, U.S. Department of Agriculture General Technical Report RMRS-RP-29, Fort Collins, CO, USDA Forest Service 66 pp.

Silvani, X., and F. Morandini. 2006. Intrusive measurement system for fire experiments at field scale. *Forest Ecology and Management,* 234, Supplement**:** S104. DOI: http://dx.doi.org/10.1016/j.foreco.2006.08.140

Silvani, X., and F. Morandini. 2009. Fire spread experiments in the field: Temperature and heat fluxes measurements. *Fire Safety Journal,* 44**:** 279-285. DOI: http://dx.doi.org/10.1016/j.firesaf.2008.06.004

Silvani, X., F. Morandini, and J. L. Dupuy. 2012. Effects of slope on fire spread observed through video images and multiple-point thermal measurements. *Experimental Thermal and Fluid Science,* 41**:** 99-111. DOI: http://dx.doi.org/10.1016/j.expthermflusci.2012.03.021

Sitch, S., B. Smith, I. C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. O. Kaplan, S. Levis, et al. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology,* 9**:** 161-185. DOI: 10.1046/j.1365-2486.2003.00569.x

Smith, B., I. C. Prentice, and M. T. Sykes. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography,* 10**:** 621-637. DOI: 10.1046/j.1466-822X.2001.t01-1-00256.x

Thonicke, K. 2010. Interactive comment on "The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model". *Biogeosciences Discussions***:** C713–C714.

Thonicke, K., A. Spessa, I. C. Prentice, S. P. Harrison, L. Dong, and C. Carmona-Moreno. 2010. The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model. *Biogeosciences,* 7**:** 1991–2011. DOI: 10.5194/bg-7-1991-2010

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer. 2001. The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography,* 10**:** 661-677. DOI: 10.1046/j.1466-822x.2001.00175.x

Vallejo, R. 1997. *The Restoration of the Vegetal Cover in Valencian Region* [in Spanish]. Valencia: Fundación Centro de Estudios Ambientales del Mediterráneo (CEAM).

Venevski, S. 2010. Interactive comment on "The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model". *Biogeosciences Discussions***:** C331–C338.

Venevsky, S., K. Thonicke, S. Sitch, and W. Cramer. 2002. Simulating fire regimes in human-dominated ecosystems: Iberian Peninsula case study. *Global Change Biology,* 8**:** 984-998. DOI: 10.1046/j.1365-2486.2002.00528.x

Wagner, C. E. V. 1977. Conditions for the start and spread of crown fire. *Canadian Journal of Forest Research,* 7**:** 23-34. DOI: 10.1139/x77-004

Weber, R. O. 2001. Chapter 5 - Wildland Fire Spread Models. In *Forest Fires,* eds. E. A. Johnson, and K. Miyanishi, 151-169 pp. San Diego: Academic Press.

Wilson Jr., R. A., 1982. A Reexamination of Fire Spread in Free-Burning Porous Fuel Beds. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-289, Ogden, Utah, USDA Forest Service 32 pp.

Wilson, R., 1980. Reformulation of forest fire spread equations in SI units. Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture General Technical Report INT-292, Ogden, Utah, USDA Forest Service 7pp.

Wright, I. A. 1997. Identifying biological constraints acting on livestock systems in marginal areas. In *Livestock Systems in Rural Development in Disadvantaged Areas*, 6. Nafplio, Greece.

9. List of published master thesis

Department of Physical Geography and Ecosystem Science, Lund University

Lund University GEM thesis series are master theses written by students of the international master program on Geo-information Science and Earth Observation for Environmental Modelling and Management (GEM). The program is a cooperation of EU universities in Iceland, the Netherlands, Poland, Sweden and UK, as well a partner university in Australia. In this series only master thesis are included of students that performed their project at Lund University. Other theses of this program are available from the ITC, the Netherlands (www.gem-msc.org or www.itc.nl).

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 2013. The complete list and electronic versions are also electronic available at the LUP student papers (www.nateko.lu.se/masterthesis) and through the Geo-library (www.geobib.lu.se).

1 Soheila Youneszadeh Jalili (2013) The effect of land use on land surface temperature in the Netherlands
2 Oskar Löfgren (2013) Using Worldview-2 satellite imagery to detect indicators of high species diversity in grasslands
3 Yang Zhou (2013) Inter-annual memory effects between Soil Moisture and NDVI in the Sahel
4 Efren Lopez Blanco (2014) Assessing the potential of embedding vegetation dynamics into a fire behaviour model: LPJ-GUESS-FARSITE