SILVA LUSITANA

Ano XXV Volume 25 nº 1 Junho de 2017

INSTITUTO NACIONAL DE INVESTIGAÇÃO AGRÁRIA E VETERINÁRIA

INSTITUTO NACIONAL DE INVESTIGAÇÃO AGRÁRIA E VETERINÁRIA

Nº Depósito Legal: 12292/86
ISSN: 0870-6352

Assinaturas: A revista é publicada com uma periodicidade semestral.

Os pedidos de assinaturas devem ser enviados para: Comissão Editorial da **SILVA LUSITANA - INIAV -** Av. da República, Quinta do Marquês 2780-157 OEIRAS, Portugal.
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Condições de assinatura, em 2017:
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Este número da **SILVA LUSITANA** teve o patrocínio de:

ASSOCIAÇÃO PORTUGUESA DA CORTIÇA

SOCIEDADE PORTUGUESA DE CIÊNCIAS FLORESTAIS

THE NAVIGATOR COMPANY

Composição: Dalila Oliveira (INIAV)
Impressão: Tipografia Lousanense
Tiragem: 300 Exemplares

SILVA LUSITANA

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Volume 25 (1)

CITADO EM/CITÉ DANS/INDEXED IN:
ISI WEB of Science, CAB International (Forestry Abstracts), EBSCO, Ecological Abstracts, IPNI, LATINDEX, National Agricultural Library (USDA)

Silva Lusitana, **25**(1): 1 - 19, 2017

Pyrolysis Behavior and Characterization of Torrefied Wood Chips

Liliana Loureiro*, Filipe Vieira de Campos* and Leonel Nunes**

Abstract. The pyrolysis behavior of torrefied wood produced in Portugal was investigated. Torrefaction is the thermochemical upgrading of biomass at approximately 300ºC in an atmosphere free of oxidizing agents to increase fuel density and to improve fuel quality, decreasing moisture and increasing heating value. Torrefied woodchips were pyrolysed at pressurized conditions in an inert atmosphere at 600ºC. All the condensable liquids were sampled for analyses. The torrefied woodchips thermogram showed a rapid devolatilization starting at approximately 300ºC. The fast pyrolysis zone was observed after 380ºC up to more or less 900ºC. Torrefied material pyrolysis yielded significantly high yields of hydrogen and methane and low amounts of carbon dioxide in the pyrolysis gas compared to normal biomass. All pyrolysis hydrocarbon liquids were analysed using simulated distillation (simdis) and gas chromatography mass spectrometry (GCMS). The GCMS analyses showed that biomass hydrocarbon liquids consisted predominantly of various types of oxygenates (oxygen containing organic compounds). The torrefied wood hydrocarbon GCMS chromatogram was less complex compared to normal wood samples. Torrefied wood hydrocarbon liquid showed higher concentrations of aliphatic aldehydes liquid. A decrease in all the other molecular components was observed for the torrefied wood hydrocarbon liquid. A significant decrease in the acid concentration was observed for the torrefied wood hydrocarbon liquid compared to non-torrefied wood. The main organic components in the torrefied wood pyrolysis water fractions were acids, alcohols and aliphatic oxygenates. The remaining organic compounds consisted of various types of oxygenates. Torrefied wood pyrolysis water exhibited showed a significantly lower acid concentration when

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compared to non-torrefied wood pyrolysis water. The biomass chars (prepared at 600ºC) were analysed using proximate analyses and carbon dioxide char reactivity. Proximate analyses showed that volatile matter was still present in the torrefied wood, but was almost completely devolatilized after pyrolysis.
Key words*:* Pyrolysis, pyrolysis compounds, chemical composition, torrefaction

Comportamento de pirólise e caracterização de aparas de madeira torrificada

Sumário. O comportamento de pirólise de madeira torrificada produzida em Portugal foi investigado. A torrefação é a conversão termoquímica da biomassa a aproximadamente 300ºC numa atmosfera sem agentes oxidantes para aumentar a densidade do combustível e melhorar a sua qualidade, diminuindo a humidade e aumentando o poder calorífico. A estilha de madeira torrificada foi pirolisada em condições pressurizadas numa atmosfera inerte a 600ºC. Todos os líquidos condensáveis foram recolhidos para análise. O termograma da biomassa torrificada mostrou uma rápida desvolatilização a partir de aproximadamente 300ºC. A zona de pirólise rápida foi observada aos 380ºC, até mais ou menos 900ºC. A pirólise do material torrificado produziu rendimentos significativos de hidrogénio e metano, e baixas quantidades de dióxido de carbono no gás de pirólise, em comparação com a biomassa normal. Todos os líquidos resultantes da condensação de hidrocarbonetos foram analisados utilizando uma destilação simulada (simdis) e espectrometria de massa por cromatografia gasosa (GCMS). As análises do GCMS mostraram que os líquidos de hidrocarbonetos de biomassa consistiam predominantemente em vários tipos de compostos oxigenados (compostos orgânicos contendo oxigénio). O cromatograma GCMS de hidrocarbonetos de madeira torrificada foi menos complexo em comparação com amostras de madeira normais. O líquido com hidrocarbonetos apresentou maiores concentrações de aldeídos alifáticos. Observou-se uma diminuição em todos os outros componentes moleculares. Observou-se uma diminuição significativa da concentração de ácidos da biomassa torrificada em comparação com a biomassa não torrificada. Os principais componentes orgânicos nas frações de água de pirólise foram ácidos, álcoois e oxigenados alifáticos. Os compostos orgânicos remanescentes consistiam em vários tipos de compostos oxigenados. A água de pirólise de biomassa torrificada mostrou uma concentração de ácido significativamente menor quando comparada à água de pirólise de biomassa não torrificada. Os carvões de biomassa (preparados a 600ºC) foram analisados utilizando análises próximas e reatividade. Análises imediatas mostraram que ainda estava presente matéria volátil na biomassa torrificada, mas foi quase completamente desvolatilizada após a pirólise.
Palavras-chave: Pirólise, compostos de pirólise, composição química, torrefação

Comportement de la pyrolyse et la caractérisation des copeaux de bois torréfié

Résumé. Le comportement de la pyrolyse du bois torréfiés produit au Portugal a été étudiée. La torréfaction est la conversion thermochimique de la biomasse à environ 300°C dans une atmosphère sans agents d'oxydation pour accroître la densité du carburant et à améliorer la qualité en réduisant l'humidité et l'augmentation de la valeur calorifique. Les copeaux de bois torréfié a été pyrolyse dans des conditions sous pression dans une atmosphère inerte à 600°C Tous les liquides condensables ont été recueillis pour analyse. Le thermogramme de la biomasse torréfiée a montré une dévolatilisation rapide d'environ 300°C. La zone de pyrolyse rapide a été observée à 380°C, jusqu'à environ 900°C La pyrolyse de la matière torréfié produire des rendements significatifs de méthane et d'hydrogène, et de faibles quantités de dioxyde de carbone dans le gaz de pyrolyse, par rapport à la biomasse normale. Tous les hydrocarbures liquides résultant de la condensation ont été analysés en utilisant une distillation simulée (SimDis) et chromatographie en phase gazeuse par spectrométrie de masse (GC-MS). L'analyse GCMS a montré que la biomasse est composée principalement d'hydrocarbures liquides dans divers types de composés oxygénés (composés organiques contenant de l'oxygène). Le chromatogramme GCMS d'hydrocarbures bois torréfié est moins complexe par rapport à des échantillons de bois normales. Les hydrocarbures liquides introduits à des concentrations plus élevées d'aldéhydes aliphatiques. Il y avait une diminution de tous les autres composants moléculaires. Il y avait une diminution significative de la concentration en acides biomasse torréfiés par rapport à la biomasse non torréfiée. Les principaux composants organiques dans les fractions de pyrolyse de l'eau sont les acides, les alcools aliphatiques et d'oxygène. Les matières organiques restantes se composait de divers types de oxygénés. La pyrolyse de la biomasse de l'eau torréfié a montré une concentration acide significativement plus faible par rapport à l'eau non torréfié pyrolyse de la biomasse. Les atomes de carbone de la biomasse (préparé à 600°C) ont été analysées en utilisant l'analyse et à proximité de la réactivité. L'analyse immédiate a montré que la matière volatile était encore présent dans la biomasse torréfiée, mais a été presque complètement dégazé après pyrolyse.

Mots-clés: Pyrolyse, les composés de la pyrolyse, la composition chimique, la torréfaction

Introduction

Biomass residues and waste are abundant potential feedstock for pyrolysis, gasification or combustion processes and seem to be an attractive alternative raw material to current fossil fuel resources (SRINIVASAN *et al.*, 2015). Pyrolysis is an attractive technology that converts biomass directly into liquid products (BRIDGWATER, 2012). However, during pyrolysis can be produced as well gaseous and solid products, depending on the residence time of the raw materials in the reactor chamber, and to the temperature choc to which raw materials are submitted.

Torrefaction can be suggested as a method of biomass pre-treatment and can be defined as the thermochemical conversion of biomass at approximately 300ºC in an inert atmosphere (NUNES *et al.*, 2014).

During biomass torrefaction, almost all moisture and a fraction of the light volatiles are removed to form a solid, dry material known as torrefied biomass (BATIDZIRAI *et al.*, 2013). The aim of torrefaction is to change the properties of biomass to obtain a better fuel quality with higher energy density, more homogeneous composition, lower hygroscopicity and elimination of biological activity (AGAR and WIHERSAARI, 2012).

In this study, torrefied biomass was produced at YGE – Yser Green Energy SA (Portugal) and characterized at Sasol Technology, Research and Development (South Africa). The experimental methods (pyrolysis and analytical methodologies) were previously established using a selection of South African biomass species.

Materials and methods

Biomass samples

Wood chips were torrefied at approximately 260-280ºC at YGE – Yser Green Energy SA in Portugal and subjected for characterization and pyrolysis studies to Sasol Technology, Research and Development in South Africa. Figure 1 shows the torrefied woody biomass chips sample, more precisely pine wood.

Figure 1 - Torrefied pine tree wood chips produced at YGE – Yser Green Energy SA (Portugal)

Fischer-tar Assay

The Fischer-tar Assay is a standard laboratory test for determining the yield of tar, water, char and gas (by difference) for a given coal (SANS 647: 1974) (GRÄBNER, 2014). The method entails the controlled heating of a defined quantity of material (50g) in an aluminum retort to a final temperature of 520ºC. The heating program used is summarized in Table 1.

Table 1 - Heating program used for Fischer-tar Assay

Time from start (minutes)	Temperature (ºC)
10	220
20	310
30	380
40	440
50	480
60	505
70	520
80	520

During this test, biomass is converted to char with release of volatile matter (ROETS *et al.*, 2014). All condensable material (tar and water) is collected in a round bottom flask submerged in ice. The water content of the condensable product is determined via a Dean and Stark distillation. The percentage of gas is obtained by difference.

Termogravimetric analysis (TGA)

TGA proximate analysis

All thermogravimetric analyses were conducted in a nitrogen atmosphere with a flow of 150 ml/min. Samples were heated from room temperature to 110ºC with a heating rate of 50ºC per minute. The samples were kept at 110ºC for three minutes. Mass loss at this temperature was assigned to moisture.

Samples were then heated from 110ºC to 900ºC with a heating rate of 50ºC per minute. The samples were kept at 900ºC for seven minutes. Mass loss at this temperature was assigned as volatile matter. This volatile matter includes liquid hydrocarbons, gas and pyrolytic water. The TGA atmosphere was then changed to oxygen (150 ml/min) and kept for 20 minutes. The mass loss due to combustion was assigned as fixed carbon. The remaining residue was recorded as the amount of ash in the sample.

TGA mass loss

All thermogravimetric mass loss analyses were conducted in a nitrogen atmosphere with a flow of 150 ml/min. Samples were devolatilized from room temperature to 900ºC at a heating rate of 10ºC per minute. The samples were kept at 900ºC for seven minutes.

TGA carbon dioxide char reactivity

Prior to char reactivity analyses, a standard proximate analysis was conducted to determine the amount of fixed carbon for a given sample. A sample containing 5mg of fixed carbon was heated in an inert atmosphere to 1200ºC with a heating rate of 50ºC per minute. The char was then allowed to cool down to 1000ºC. When the temperature and mass were stabilized, the inert gas was replaced with carbon dioxide. The Boudouard reaction (JIAO *et al.*, 2015) was allowed to continue until no further mass loss was observed. The calculation of the carbon dioxide char reactivity at 60% burn-off is discussed in literature (DEL-CAMPO *et al.*, 2015; CHOI *et al.*, 2015; GUIZANI *et al.*, 2014; ALVAREZ *et al.*, 2014).

Pyrolysis experiments

The standard Koekebakker™ setup was used for biomass pyrolysis (MILLER, 2011). All experiments were conducted at atmospheric pressure in a nitrogen atmosphere. The Koekebakker™ was loaded with approximately 150 to 400g of biomass prior to pyrolysis. During the pyrolysis experiments, two hydrocarbon liquid fractions were collected: condensed oil and additional oil.

A condenser connected to a chiller was connected to the outlet of the reactor. The condenser was connected to a two-neck round-bottom flask immersed in an acetone/ice bath. Connected to the round-bottom flask were four solvent traps in series (three traps filled with solvent and a final empty trap). With one exception, all the solvent traps were immersed in ice/acetone baths. The solvent traps were filled with acetone for both quantity and quality experiments. All involved gases were captured in a bag after the solvent traps. All pyrolysis experiments were conducted at 600ºC with a heating rate of ~10ºC per minute.

<u>Determination of water content in the liquid hydrocarbon</u>

Toluene was added to the liquid product in the round-bottom flask and Dean-Stark distilled to quantitatively determine the amount of water. The condenser and all pipes were washed with acetone. All acetone fractions (solvent traps and acetone from washed pipes) were added together. The acetone was removed from the hydrocarbon liquid by distillation.

<u>Determination of liquid hydrocarbon quality</u>

Chloroform was added to the condensate in the round-bottom flask and transferred to a separation funnel. The organic phase was removed from the water phase. The condenser and all pipes were washed with acetone. Solvents were removed from the hydrocarbon liquid by distillation.

Characterization of liquid hydrocarbons

Simulated distillation (simdis)

Simulated distillation was conducted on a high-temperature GC-FID fitted with an ARX 2887 Restek column (10m x 0.53mm x 0.53μm). Approximately a 0.2μL sample was injected into the GC column per analysis. The GC oven program started with an initial temperature of 40ºC, then heated at 15ºC per minute to 540ºC and hold at that temperature for 10 minutes.

Gas chromatography mass spectrometry (GCMS)

All oil samples were analyzed using a GC-FID (quantification) and a GCMS (peak identification) fitted with HP-FFAP column (50m x 0.2mm x 0.33μm). The HP-FFAP column is a high polarity column suited for the analyses of organic acids, free fatty acids and phenols. Approximately 1μL of sample was injected into GC column with a split of 200 (if samples were too diluted a split of a 100 was used). The GC oven program was as follows: initial temperature of 60ºC held for 5 minutes, heating at 6ºC per minute to 240ºC and hold for 30 minutes (until all compounds were eluted). Gas flow through the column was 1.2ml per minute (helium in GCMS and hydrogen in GC-FID).

Two-dimensional gas chromatography mass spectrometry

Two-dimensional gas chromatography mass spectrometry (hereafter GCxGCxMS) was conducted on a Leco GCxGC TOF fitted with a Restek Stabilwax column (60m x 0.25mm x 0.25μm) and Restek RTXi5 column (2m x 0.1mm x 0.1μm). Approximately 0.5μL of sample was injected into the GC column with a split of 400. Helium gas flow through the column was 1.3ml per minute. The GC oven program for column 1 was as follows: initial temperature of 40ºC held for 1 minute, heating at 2ºC per minute to 230ºC. The GC oven program for column 2 was as follows: initial temperature of 65ºC held for 1 minute and heating at 2ºC per minute to 255ºC.

Results and discussion

Characterization of biomass

Proximate analyses

Biomass samples were air-dried and crushed to <150μm for proximate analyses and the results are presented in Table 2. During torrefaction, all moisture and light volatiles are removed from the biomass.

Table 2 - Proximate analyses results for torrefied biomass

	Air-dry basis	Dry basis			Dry, ash-free basis	
Sample	**% Moisture**	**% VM**	**% FC**	**% Ash**	**% VM**	**% FC**
Torrefied wood	4.4	62.4	36.4	1.2	63.2	36.8

VM – Volatile matter; FC – Fixed carbon

Thermochemical behavior (TGA devolatilization)

The combined devolatilization profiles (thermograms) are presented in Figure 2. The individual devolatilization profiles are presented in Figure 3. The first derivative of the mass loss curve was determined to observe the thermal behavior of these biomass samples (Figure 3).

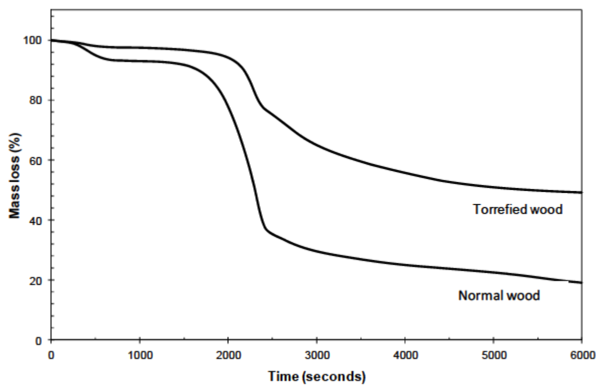

Figure 2 - Devolatilization profiles (thermograms) of torrefied and normal wood

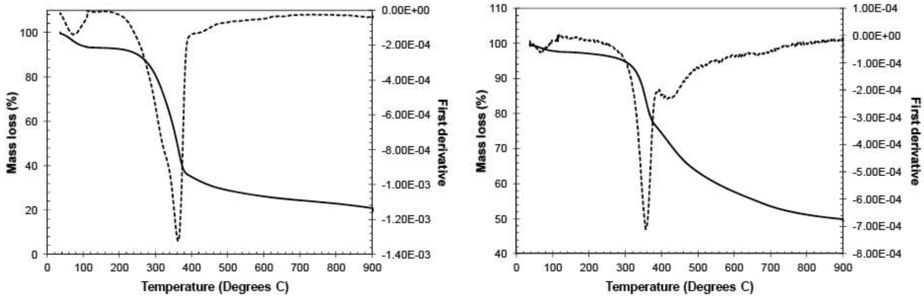

Figure 3 - Individual devolatilization profiles (thermograms) of normal wood (left) and torrefied wood (right)

The thermograms in Figures 2 and 3 exhibited an initial mass loss ending at 110ºC. This mass loss was assigned as moisture associated with the sample. The un-torrefied wood thermogram showed a rapid devolatilization starting at approximately 230ºC and ending at approximately 370ºC (fast pyrolysis zone). A slow mass loss was still observed after 370ºC for this biomass sample (slow pyrolysis zone).

The first derivative of the mass loss curve showed that there were two thermal events occurring during fast pyrolysis (between 230ºC to 370ºC). These events could be attributed to the decomposition of hemicellulose and cellulose polymers in the biomass samples (CABEZA *et al.,* 2016). The first event was associated with hemicellulose decomposition that typically occurs at relatively low temperatures (~200ºC) (KIHEDU, 2015). The second thermal event was associated with cellulose decomposition (typical decomposition temperature of 315 to 400ºC) (ASHWORTH *et al.,* 2014). The slow pyrolysis observed was associated with the slow decomposition of lignin (from 370 to 900ºC) (DENG *et al.,* 2009).

The torrefied wood thermogram showed a rapid devolatilization starting at approximately 300ºC due mainly to hemicellulose degradation. The fast pyrolysis zone was observed between 300ºC and 380ºC (assigned to the decomposition of remnant cellulose). A slightly slower mass loss was still observed after 380ºC up to 900ºC (assigned to the decomposition of remnant lignin).

Pyrolysis of biomass (product quality and quantity)

<u>Pyrolysis yields</u>

Results from Fischer-tar Assay for yields torrefied biomass are summarized in Table 3.

Table 3 - Fischer-tar Assay for torrefied biomass

Product	**Torrefied Wood**
% Char	44.7
% Tar	16.2
% Water	20.4
% Gas	18.7
Total	100.0

% Gas is determined by difference

Results of pyrolysis products are shown in Table 4. As mentioned above, in the section Pyrolysis experiments, water and oil condensates, consist of all the oil condensed in the ice-acetone cooled round-bottom flask. Additional oil consists of oil isolated from the four solvent traps and oil washed from the condenser and pipes.

Table 4 - Quantitative pyrolysis results for torrefied biomass

Sample	**Torrefied wood**
% Char	43.2 (0.12)
% Hydrocarbon liquid	14.0 (0.98)
% Water	20.3 (1.06)
% Gas	22.6 (0.20)
Total	**100.0**

% Gas is determined by difference. Standard deviation is shown in parentheses.

The torrefied wood still yields a significant amount of water during pyrolysis. This is pyrolytic water formed from the thermal decomposition of the oxygen functionality present in the molecular structure of biomass.

Pyrolysis gas characterization

Pyrolysis gas was collected during the pyrolysis experiments (bag samples) and analyzed using gas chromatography. All experiments were conducted in a nitrogen atmosphere. Therefore data were normalized to a nitrogen-free basis. The gas compositions of the various pyrolysis experiments are shown in Table 5.

Table 5 - Pyrolysis gas composition of torrefied wood

	Torrefied wood
Other (C2+)	2.3
Oxygen/Argon	2.9
Carbon dioxide	22.5
Carbon monoxide	30.1
Methane	22.0
Hydrogen	20.1

The torrefied wood pyrolysis gas composition differed significantly in comparison to usual normal wood. Torrefied wood pyrolysis yielded significantly high amounts of hydrogen (~20%) and methane (~22%). Carbon dioxide and carbon monoxide are formed from the thermal decomposition of the oxygen remaining in the molecular structure of biomass. Torrefaction removed a significant amount of oxygen atoms or radicals from the molecular structure of biomass. Therefore less oxygen was available for the formation of carbon monoxide and carbon dioxide.

Characterization of biomass liquid hydrocarbons

As aforementioned, two types of hydrocarbon liquids were collected during the pyrolysis experiments: condensed oil and additional oil. These two hydrocarbon liquid fractions were mixed together to form a homogeneous hydrocarbon sample for analysis.

Simulated distillation of biomass liquid hydrocarbons

Simulated distillations (simdis) (ROETS *et al.*, 2015) were conducted to determine the boiling point distributions of all the biomass liquid hydrocarbons (Figure 4).

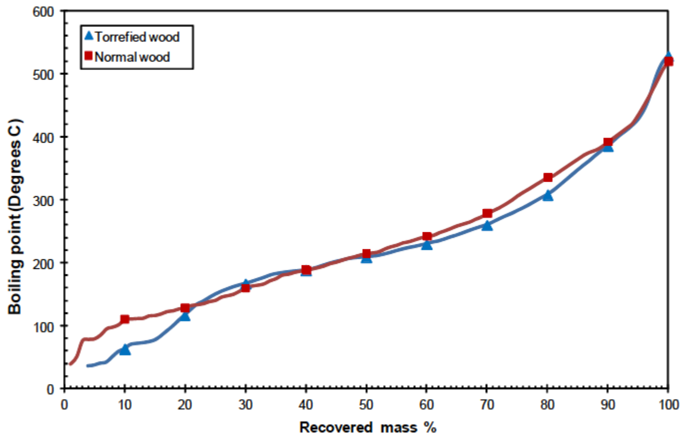

Figure 4 - Simulated distillation results for torrefied wood and normal wood

The weight average boiling points (WABP) of the simulated distillation curves were calculated (Equation 1) for comparison. Results are summarized in Table 6.

$$WABP = \frac{T_{10wt\%}+T_{30wt\%}+T_{50wt\%}+T_{70wt\%}+T_{90wt\%}}{5} \quad \text{(Equation 1)}$$

Table 6 - Weight average boiling points from simulated distillation curves

Sample	Torrefied wood
WABP (ºC)	216.5

From these simulated distillations, was concluded that torrefied wood hydrocarbon liquid and normal wood hydrocarbons liquids had similar boiling point distribution, with torrefied wood liquid being slightly smaller.

Gas chromatography mass spectrometry of biomass liquid hydrocarbons

The GCMS profiles of the hydrocarbon liquids consisted of various types of oxygenates (oxygen containing organic compounds). To simplify the chromatographic data, the compounds were grouped according to specific molecular families. These families included: aliphatic hydrocarbons, acids, aliphatic esters, aliphatic aldehydes and ketones, aliphatic alcohols, alkylbenzenes, alkylphenols, furans (with polyfunctional oxygen), linear and cyclic aliphatic oxygenates (polyfunctional oxygen), aromatic oxygenates (polyfunctional oxygen) and nitrogen/sulphur containing compounds.

The percentage of each molecular family for each biomass sample was determined and is summarized in Table 7.

Table 7 - GCMS analytical results for composition of the various hydrocarbon liquid fraction in torrefied biomass

Molecular component	Torrefied wood
Aliphatic	0.57
Acids	2.24
Aliphatic ester	0.00
Aliphatic aldehydes and ketones	33.32
Aliphatic alcohol	0.00
Alkylbenzenes	2.07
Alkylphenol	35.83
Furan	0.70
Furan (polyfunctional oxygen)	5.90
Linear and cyclic aliphatic oxygenates (polyfunctional oxygen)	6.61
Aromatic oxygenates (polyfunctional oxygen)	12.25
Nitrogen and sulphur containing compounds	0.51
Total	**100.0**

The amount of unknown compounds observed in the GC chromatograms was 22.9% for torrefied biomass.

The torrefied wood hydrocarbon GCMS chromatogram was less complex when compared to normal wood. The normal wood chromatogram consisted of 125 compounds, whereas the torrefied wood chromatogram consisted of 56 compounds (excluding the unknown peaks). This decrease in hydrocarbon complexity was expected since torrefaction removes most of the light hydrocarbons and acids from the solid biomass. Torrefied wood hydrocarbon liquid showed higher concentrations of aliphatic aldehydes, ketones and alkylphenol when compared to normal wood hydrocarbon liquid. A decrease in all the other components was observed for the torrefied wood hydrocarbon liquid when compared to the normal wood sample. The main advantage of torrefaction was the decrease in the acid concentrations when compared to normal wood.

GSMS analytical results for pyrolysis water fraction of torrefied biomass

The pyrolysis water and oil were separated using a separation funnel after each pyrolysis experiment. The water fractions were collected and analyzed using GCMS. The organic compounds present in the water phase fraction are summarized in Table 8.

Note that the quantification of the amount of organics in the water was not conducted due to water added during the separation step to distinguish between the two phases (this was due to discoloration of the water phase).

Table 8 - GCMS composition results of organic compounds for the pyrolysis water faction in torrefied biomass

Component	Torrefied wood
Acids	27.31
Aliphatic hydrocarbons	1.39
Aliphatic alcohol	21.41
Aliphatic aldehydes and ketones	9.05
Alkylphenols	7.26
Aromatic oxygenates	3.50
Aliphatic oxygenates	25.84
Furan oxygenates	4.23
Nitrogen heteroatoms	0.00
Total	**100.0**

Data was normalized to 100% organic composition

The main organic components in both normal wood and torrefied wood pyrolysis water fractions were acids, alcohols and aliphatic oxygenates. The remaining organic compounds consisted of various types of oxygenates. Torrefied wood pyrolysis water exhibited a significantly lower acid concentration when compared to normal wood pyrolysis water.

Pyrolysis char proximate analysis and reactivity

Results of char proximate analysis are summarized in Table 9.

Table 9 - Proximate analysis of biomass chars (600ºC chars)

	Dry, ash-free basis	
Sample	**% VM**	**% FC**
Normal wood	18.7	81.3
Torrefied wood	5.9	94.1

Proximate analyses of the normal wood chars showed that volatile matter was still present. This was expected when evaluating the devolatilization profiles of the normal wood sample. Although devolatilization stops at approximately 370ºC there was still slow mass loss up to 900ºC.

The carbon dioxide gasification reactivity of the fixed carbon at 50% burn-off was determined using the pyrolysis biomass chars. The results are summarized in Table 10.

Table 10 - Carbon dioxide reactivity of biomass chars (TGA)

Sample	TGA CO2 char reactivity
Normal wood	10.5
Torrefied wood	17.1

Conclusions

The pyrolysis behavior of torrefied wood was investigated. Torrefaction is the thermochemical upgrading of biomass at approximately 200 to 320ºC (inert atmosphere) to increase the fuel quality. Torrefied wood was pyrolysed at atmospheric pressure (nitrogen atmosphere) at 600ºC. All the condensable liquids (water and oil) were sampled for detailed analyses. The pyrolysis behavior of torrefied wood was compared to normal wood pyrolysis.

Comparison between normal wood and torrefied wood samples:

- Proximate analyses showed that normal wood and torrefied wood were significantly different in composition. Normal wood had a higher volatile matter content compared to torrefied wood, as expected.
- Thermogravimetric analyses (devolatilization profiles) of normal wood showed rapid devolatilization starting at ±230ºC and ending at ±370ºC (fast pyrolysis zone). A slow mass loss was still observed after 370ºC

(slow pyrolysis zone). The torrefied wood thermogram showed a rapid devolatilization starting at approximately 300ºC. The fast pyrolysis zone was observed between 300ºC and 380ºC. A slightly slower mass loss was still observed after 380ºC up to 900ºC. The mass loss in terrified biomass TGA was lower than that of normal biomass, as expected, due torrefaction changes.

- The normal wood sample exhibited the highest hydrocarbon liquid yield, followed by the torrefied sample.
- The torrefied wood pyrolysis gas composition differed significantly in comparison to normal wood sample. Torrefied wood pyrolysis yielded significantly higher amounts of hydrogen and methane and significantly lower amounts of carbon dioxide.
- Torrefied and normal woody biomass hydrocarbon liquid fractions were similar in boiling temperature distribution, with torrefied wood liquid being slightly smaller. The torrefied wood hydrocarbon GCMS chromatogram was less complex when compared to the normal wood sample, reflecting a significant difference between the two woody biomasses. Torrefied wood hydrocarbon liquid exhibited higher concentrations of aliphatic aldehydes and ketones and alkylphenol when compared to the wood hydrocarbon liquid. A decrease in all the other molecular components was observed for the torrefied wood hydrocarbon liquid. The GCMS analyses showed that normal biomass hydrocarbon liquids consisted predominantly of various types of oxygenates (oxygen containing organic compounds). A significant decrease in the acid concentration was also observed for the torrefied woody biomass hydrocarbon liquid.
- The main organic components in both normal wood and torrefied wood pyrolysis water fractions were acids, alcohols and aliphatic oxygenates. The remaining organic compounds consisted of various types of oxygenates. Torrefied wood pyrolysis water exhibited a significantly lower acid concentration when compared to the normal wood pyrolysis water.
- The biomass chars were analyzed using proximate analyses and carbon dioxide char reactivity. Proximate analyses showed that volatile matter was still present in the normal wood chars. Torrefied wood, however, was almost completely devolatilized after pyrolysis.

Acknowledgements

The authors would like to acknowledge Sasol Technology, Research and Development in particular to Rudy Coetzer for processing the biomass samples and also for all the Koekebakker™ pyrolysis work, Ben Ashton for all the thermogravimetric analyses, Neil de Beer for all the gas analyses, Mariska Freyer and Michael Moeketsi for all the GCMS and GC-FID analyses, Rene Engelbrecht for all the simulated distillation analyses, Heinn Potgieter for the two-dimensional GCMS analyses and to Johan van Dyk and Daniel van Niekerk for the elaboration of the analytical report.

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Entregue para publicação em abril de 2017
Aceite para publicação em junho de 2017

Silva Lusitana, **25**(1): 21 - 30, 2017

Exploratory Study on the Feasibility of Producing Mixed Finger Joints from Hardwoods

Ajit Kumar, V.S. Kishan Kumar and Sachin Gupta

Abstract. This paper tries to investigate the possibility of using up short sections of two hardwoods to make finger jointed sections. Finger jointed samples of *Melia azedarach* and Eucalyptus using UF adhesive showed noticeable improvements in bending strength compared to the finger jointed sections of *M. azedarach* alone. The mixed sections also exhibited higher MOE values than those of joint-free and finger-jointed *M. azedarach* sections. Overall, the study illustrated the possibility of using short pieces of *M. azedarach* sections along with those of eucalyptus through finger jointing technique.
Key words: Bending strength, Finger-joint, Eucalyptus, *Melia azedarach*, MOE, urea formaldehyde

Estudo exploratório sobre a possibilidade de produção de encaixes mistos de madeira de folhosas

Sumário. Este artigo visa investigar a possibilidade de usar seções curtas de dois tipos de madeira de folhosas para a produção de encaixes de madeira. Amostras com encaixes de *Melia azedarach* e de *Eucalyptus* sp. com utilização de adesivo UF evidenciaram uma melhoria considerável na resistência à flexão em comparação com os encaixes utilizando apenas madeira de *M. azedarach*. As seções mistas também exibiram valores MOE mais elevados do que os das seções com apenas *M. azedarach* sem encaixes e com encaixes. Em geral, o estudo ilustrou a possibilidade de usar peças curtas de secções de *M. azedarach* juntamente com as do eucalipto graças à produção de encaixes.
Palavras-chave: Força de flexão, encaixe de madeira, *Eucalyptus*, *Melia azedarach*, MOE, ureia-formaldeído

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Étude exploratoire sur la possibilité de la production de jonction mixte par enture à partir des feuillus

Cet article vise à étudier la possibilité d'utiliser des sections courtes de deux feuillus pour faire des sections jointes par enture. Les échantillons joints par enture de *Melia azedarach* et d'*Eucalyptus* sp. en utilisant de l'adhésif UF ont montré des améliorations remarquables de la résistance à la flexion par rapport aux sections jointes par enture en utilisant seulement *M. azedarach*. Les sections mixtes ont également affiché des valeurs MOE plus élevées que celles des sections sans et avec entures de *M. azedarach* uniquement. Dans l'ensemble, l'étude a illustré la possibilité d'utiliser de courts morceaux de sections de *M. azedarach* avec ceux de l'eucalyptus grâce à la technique de jonction par enture.

Mots-clés: Force de flexion, jointure en bois, *Eucalyptus*, *Melia azedarach*, MOE, urée-formaldéhyde

Introduction

Wood exhibits its greatest strength parallel to its grain. However, development of end joints that can transmit a significant proportion of this strength has always been challenging and at times difficult. Finger-jointing has proven to be one successful technique to achieve this which also contributes heavily to better utilization of wood residues. These joints were suggested to be used for structural members based on estimation of fatigue strength of such joints (BOHANNAN and KANVIK, 1969). Finger joints with 64 -97% bending and tensile strengths compared to solid wood have been reported (JANOWIAK *et al*., 1993). Finger joints of mango wood with UF adhesive exhibited similar bending strength and better crushing strength compared to that of solid sections (Kishan KUMAR *et al*., 2015). It is pertinent to note that almost all of the reports on finger jointed sections deal with single species.

Eucalyptus hybrid has been classified as a moderate timber with respect to its weight, strength and toughness and is reported to be suitable for construction, joinery furniture, packing cases, crates, dunnage pallets, tool handles, wood poles, fence posts, mine props and poles (SEKHAR and RAJPUT 1968; SEKHAR and GULATI, 1972). Its machining properties are also reported to be comparable to teak (JAITLY *et al*., 1983). However, problems associated with conventional drying of timber from different Eucalyptus species due to drying stresses are well known (RESCH and HANSMANN, 2002). This leads to a situation in which sufficient lengths of this timber is not readily available and finger joints can offer a solution.

Melia azedarach, commonly known as white cedar or Indian lilac, belongs to the mahogany family, *Meliaceae*. The main utility of this species is as timber which is of medium density and ranges in colour from light brown to dark red. The timber utilization extends from manufacturing of boxes and crates, fixtures, furniture to plywood. The Indian wood insect database describes the timber of this species as durable and resistant to termites (icfre.org:8080/woodsci/ /Wooddetails.jsp?id=643). Some reports are available on its cell wall structure and the ability of its vessels and fibres to return to their normal patterns after the wood is cut and the wounding effect ceases (PANDALAI *et al*., 1985; YADUN and ALONI, 1993).

Materials and methods

Sample sections were cut from kiln-seasoned (up to 10-12%) 51 mm thick planks of *M. azedarach* and Eucalyptus wood using a circular saw. Adequately long sections for jointing purposes were cut from the planks. Separate clear wood samples also were cut from the planks for using as controls. The number of samples for the measurements was seven for each type (2 clear woods and three finger jointed sets). The sample sizes were kept as of roughly 50 x 50 mm^2 cross section with 750 mm length. Fingers of 20 mm length, 5 mm pitch, 1 mm tip thickness were profiled using a standard commercial finger shaping machine. The profiled fingers were joined using a commercial Urea Formaldehyde (UF) resin. The adhesive was prepared from the UF resin powder by mixing it with 2% of ammonium chloride (NH_4Cl) hardener and making an aqueous solution with 57.6 % solid content. The prepared glue was applied to all fingers using a brush after the fingers were profiled. The finger profiled sections were joined and pressed at an end-pressure of 6 N/mm^2 on a pneumatic press. The jointed samples were made in such a way that the joints occupied their central position. The jointed samples were cured at room temperature for at least 48 hours. Prior to the bending measurements, the samples were given a light planing to remove any surplus adhesive.

The static bending measurements on the clear and jointed samples were carried out on a Universal testing machine following the broad directions laid down in Indian standards IS: 1708 (BIS, 1986). Central loading was adopted to make the bending measurements. The loading was done in a horizontal mode to the jointed specimens with fingers being parallel to the face on which the load was applied. The span of the test was kept at 700 mm. The load was applied continuously such that the movable head moved at 2.5 mm per minute and deflections were noted against applied loads until the joint failed. From the load-deflection graphs on a spread sheet, the load and deflection at the limit of proportionality were recorded.

The Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) were calculated for each sample using the following formulae:

$$MOR = \frac{3P'l}{2bh^2} \quad \text{N/mm}^2 \tag{1}$$

$$MOE = \frac{Pl^3}{4Dbh^3} \quad \text{N/mm}^2 \tag{2}$$

Where
P = Load at limit of proportionality (N)
P′ = Maximum load at which the sample/joint failed (N)
l = Span of sample (mm)
b = Breadth of sample (mm)
h = Height (thickness) of sample (mm)
D = Deflection at limit of proportionality (mm)

Data were recorded for both jointed and unjointed (clear wood) samples. The efficiencies of jointed samples were calculated as percentages of corresponding strength values of the clear wood (CW) samples.

Results and Discussion

None of the twenty one finger jointed samples exhibited wood failure away from the joint during the bending measurements. This suggests that that the strengths of the jointed sections are less than that of the clear woods of both *M. azedarach* and Eucalyptus (LARA-BOCANEGRA *et al.,* 2017). An example is given in figure 1 wherein a finger-jointed sample of Eucalyptus sections is shown under bending test. It can be clearly seen that the fingers are getting separated due to glue line failure between adjacent fingers.

Figure 1 - Photo of a finger-jointed Eucalyptus section under bending test
The results of static bending parameters obtained on the five sets of samples are given in Table 1

Table 1 -Means of Static bending parameters of samples studied

Bending Parameter		MAC	MAFJ	EuC	EuFJ	Mx
No. of samples ➔		7	7	7	7	7
MOR (N/mm²)	Mean	52.6	32.7	94.7	63.7	34.0
	SD	7.8	8.3	17.1	13.7	9.1
	CV (%)	14.8	25.5	18.0	21.5	26.8
MOE (N/mm²)	Mean	6826	6752	12907	12085	8280
	SD	815	713	2105	2056	713
	CV (%)	11.9	10.6	16.3	17.0	8.6

Note:

- MAC refers to control samples of *M. azedarach*
- MAFJ refers to finger jointed samples of *M. azedarach*
- EuC refers to control samples of Eucalyptus
- EuFJ refers to finger jointed samples of Eucalyptus
- Mx refers to finger jointed samples made with *M. azedarach* and Eucalyptus

The bending strengths (MOR) of the unjointed samples of *M. azedarach* used in the study ranged from 44.3 N/mm² to 63 N/mm². The finger jointed samples yielded bending strength values ranging from 18.6 N/mm² to 45.7 N/mm². The mean values of MOR reported in literature for *M. azedarach* clear wood are around 80 N/mm² (SHUKLA *et al.*, 1990). Thus, the present lot with a mean of 52.6 N/mm² looks to be rather inferior lot. In the case of Eucalyptus these values were 72.4 N/mm² to 129 N/mm² and 45.8 N/mm² to 81.2 N/mm² respectively for clear wood and finger jointed samples. The reported MOR value of Eucalyptus is 88.8 N/mm² (KISHAN KUMAR *et al.*, 2013). The present value of 94.7 N/mm² is actually better than this value. The sections joined with and *M. azedarach* and Eucalyptus resulted in values in MOR in the range of 22.5 N/mm² to 47 N/mm². The mean MOR values are given in figure 2.

The data on MOR were analysed using one way ANOVA and it was found that the values differ significantly ($p < 0.001$). Duncan's homogeneity test showed that the jointed samples of either species had significantly lesser MOR compared to their respective controls. Lower retentions of finger jointed Eucalyptus (34% to 42 %) depending on the finger profiles have already been reported (KISHAN KUMAR *et al.*, 2013). Though the mixed joints showed least MOR, the mean value was equal to that provided by the finger jointed sections of *M. azedarach* alone.

A similar analysis was carried out on the MOE values also. The mean values are shown in figure 3.

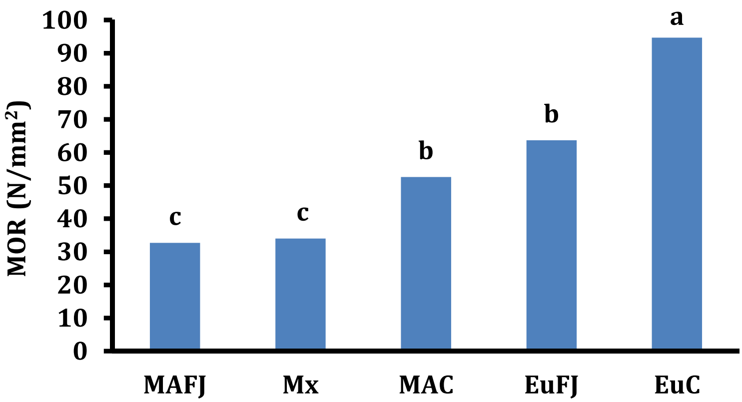

Figure 2 - The Mean MOR of the different sets of samples studied
Note: Different alphabets on the bars represent different levels of significance

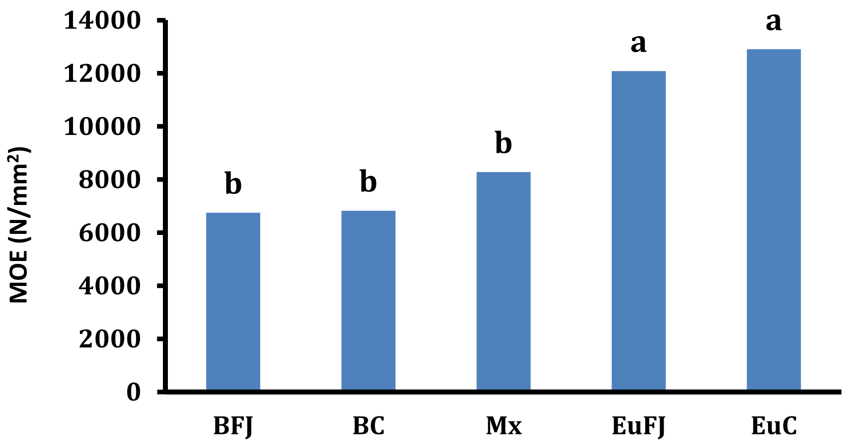

Figure 3 - The Mean MOE of the different sets of samples studied

The data analysis showed that that the values differ significantly ($p < 0.001$). Duncan's homogeneity test revealed that the jointed samples of either species had similar MOE compared to their respective clear wood unlike MOR.

However, the MOE values of Eucalyptus samples were significantly higher than those of *M. azedarach*. High retentions of MOE of finger-jointed sections of African hardwoods using resorcinol-formaldehyde, Mango wood and eucalyptus joined with UF adhesive are already reported (AYARKWA *et al.*, 2000; KISHAN KUMAR *et al.*, 2011; KISHAN KUMAR *et al.*, 2013). In the present study, the mixed joints showed MOE values similar to those of *M. azedarach* sections. MOE is considered a good indicator for predicting bending strength and the use of *E. globulus* in structural applications also has been demonstrated (SANTOS and PINHO, 2004).

Thus one can see that it is possible to use up short sections of *M. azedarach* and Eucalyptus for uses where MOR and MOE of finger jointed *M. azedarach* sections are sufficient.

Table 2 gives the efficiencies of the three finger joints studied with respect to different types of sections calculated as the percentage of MOR and MOE values over the corresponding values of the sections that are being compared with.

Table 2 - Efficiencies of the different finger joints

Parameter	MA Eff. (%)	Eu Eff. (%)	Mx Eff. Wrt MA (%)	Mx Eff. Wrt MAFJ (%)	Mx Eff. Wrt Eu (%)	Mx Eff. Wrt EuFJ (%)
MOR	62.2	67.3	64.6	104.0	35.9	53.4
MOE	98.9	93.6	121.3	122.6	64.2	68.5

Note:

- MA Eff. (%) refers to the % Efficiency of the finger-jointed samples of *M. azedarach* with respect to the corresponding control samples
- Eu Eff. (%) refers to the % Efficiency of the finger-jointed samples of Eucalyptus with respect to the corresponding control samples
- Mx Eff. Wrt MAC (%) refers to the % Efficiency of the mixed finger-jointed samples with respect to the control samples of *M. azedarach*
- Mx Eff. Wrt MAFJ (%) refers to the % Efficiency of the mixed finger-jointed samples with respect to the finger-jointed samples of *M. azedarach*
- Mx Eff. Wrt EuC (%) refers to the % Efficiency of the mixed finger-jointed samples with respect to the control samples of Eucalyptus
- Mx Eff. Wrt EuFJ (%) refers to the % Efficiency of the mixed finger-jointed samples with respect to the finger-jointed samples of Eucalyptus

Table 2 reveals that the efficiency of MOE and MOR (121.3% and 64.6%) of mixed samples are better or similar to corresponding values of finger jointed *M. azedarach* sections (98.9% and 62.2% respectively) with respect to its solid sections. Thus, mixing of Eucalyptus section with *M. azedarach* has actually contributed to better stiffness to the jointed sections. However, the mixed joints are no match to the strong Eucalyptus clear wood. On the other hand, the mixed sections show almost similar MOR efficiency (104%) as that of finger jointed *M. azedarach* sections. Compared to finger jointed sections eucalyptus alone, the efficiency in MOR of mixed sections is enhanced by 53.4%. The MOE value is 122.6% better than that of finger joined *M. azedarach* samples which is almost same improvement as that compared to joint-free samples of the species. A similar performance is seen with Eucalyptus also (Table 2). It is pertinent to note that high retention of MOE is characteristic of finger joints for many species (AYARKWA *et al*., 2000; KISHAN KUMAR *et al*., 2011; VASSILIOU *et al*., 2007).

Conclusions

Finger jointed samples of the two hardwoods studied show significantly lesser MOR compared to their respective joint-free sections. The reduction in MOR is more than 30%. However, the MOE values of jointed sections are more than 90% of the respective unjointed sections. The mixed joints showed noticeable improvements in MOR compared to the finger jointed sections of *M. azedarach* alone. The elasticities of mixed sections were much higher than those of joint-free and finger-jointed *M. azedarach* sections. Overall, the possibility of using short pieces of *M. azedarach* sections along with the short sections of eucalyptus (which otherwise might go waste) is illustrated in this study for appropriate uses.

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Entregue para publicação em janeiro de 2016
Aceite para publicação em junho de 2017

Silva Lusitana, **25**(1): 31 - 49, 2017 31
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Evaluation of an Operation of Burning of Wheat Straw Batches in a Pilot Scale Facility in Denmark

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Abstract. Two experimental trials of burning of 200kg wheat straw batches, with an energy content of 840kWh, were performed in April 3 and April 4 of 2017, lasting by 344mins and 315mins., in a 125kW combustion pilot scale boiler at the Foulum campus of Aarhus University in Denmark. The forwardness of combustion, with a 500m^3 of primary and secondary air inflow per hour, was monitored by continuous measurements of temperature and oxygen and carbon monoxide emissions in flue gases. The flue gases were cooled by heat exchange with water flowing in pipes around the boiler. The exchanged heat measured was 700kWh, allowing to estimate an energetic combustion efficiency of 83%. The harmful emissions of carbon monoxide obtained in the two trials averaged 365ppm and 58ppm, values which are environmentally acceptable. The energy efficiency and emission results compared favorably with other combustion experiments with boilers of lower dimension and different kind of agricultural biomasses. Carbon monoxide emissions were low and steady with peaks mainly in the beginning and in the end of the experiments. Particle emissions in the April 3 trial were also measured, reporting an average of 455mgnm^{-3}. A detailed analysis of the processes indicated that the implemented optimization of instrumentation and of the mechanisms for input of primary and secondary air, allowed providing an adequate performance of the boiler.

Key words: Boiler, straw, carbon monoxide, oxygen, particles, temperature, flue gas, efficiency

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Avaliação de uma Operação de Queima de Lotes de Palha de Trigo em uma Instalação à Escala Piloto na Dinamarca

Sumário. Dos ensaios experimentais com fardos de 200 kg de palha de trigo, com um conteúdo energético de 840kWh, foram desenvolvidos em 3 e 4 de Abril de 2017, com a duração de 344mins. e 315mins. num queimador à escala piloto, de 125kW, em instalações no campus de Foulum da Universidade de Aarhus na Dinamarca. A evolução da combustão, com um caudal de ar primário secundário de 500m^3 por hora, foi monitorizada através de medições contínuas de temperatura e emissões de oxigénio e monóxido de carbono nos gases de escape. Os gases de escape foram arrefecidos por troca de calor com água numa caldeira de circulação tubular em torno do queimador. Essa troca de calor medida foi de 700kWh, permitindo uma estimativa da eficiência da combustão em 83%. As emissões médias nefastas de monóxido de carbono nos dois ensaios foram de 365ppm e 58ppm, valores considerados aceitáveis dum ponto de vista ambiental. A eficiência energética e os resultados das emissões comparam favoravelmente com experimentações similares com outros tipos de biomassa agrícola e mesmo com queimadores de menor dimensão. As emissões de monóxido de carbono foram baixas e estáveis com picos episódicos no início e no termo das operações. As emissões de partículas na experiência de 3 de Abril foram também medidas, registando uma média de 455 mgnm^{-3}. Uma análise detalhada da evolução temporal das experiências de queima, permitiu concluir que a instrumentação e os mecanismos de fornecimento de ar primário e secundário estavam otimizados para possibilitar um adequado funcionamento do queimador.

Palavras-chave: Queimador, palha, monóxido de carbono, oxigénio, partículas, temperatura, gás de escape, eficiência

Évaluation d'une Opération de Brûlage des Lots de Paille de Blé dans un Établissement de l'Échelle Pilote au Danemark

Résumé. Deux essais expérimentaux de embrasement des lots de 200kg de paille de blé, avec un teneur en énergie de 840kWh, étaient effectués les 3 avril et 4 avril 2017, avec une duration de 344mins et 315mins. Les essays étaient réalisées dans une chaudière de 125kW au campus de Foulum de l'Université d'Aarhus au Danemark. L'avancement de la combustion, avec un 500m^3 à l'heure d'afflux d'air primaire et secondaire, a été suivie par des mesures en continu des émissions de monoxyde de carbone et d'oxygène et de température dans le gaz de efflux. Le gaz d'efflux a été refroidi par échange thermique avec l'eau qui coule dans les tuyaux autour de la chaudière. La chaleur échangée mesurée était 700kWh, ce qui permet d'estimer un rendement de combustion énergique de 83%. Les émissions nocives de monoxyde de carbone obtenu dans les deux essais ont été en moyen de 365ppm et 58ppm, valeurs qui sont acceptables sous le point de vue environnementale. L'efficacité énergétique et les résultats de l'émissions ont comparé favorablement à d'autres expériences de combustion avec différents types de biomasse agricole et dans certains cas en chaudières de dimension inférieure. Les émissions de monoxyde de carbone ont été faibles et stables avec pics principalement aux débuts au début et à la fin des expériences. Les émissions de particules sur léxperience de 3 avril ont été également mesurées, avec un résultat moyen de 455 $mgnm^{-3}$. Une analyse détaillée des processus a indiqué que la mise en œuvre de l'optimisation de l’instrumentation et des mécanismes d'entrée d'air primaire et secondaire a permis fournissant une performance adéquate de la chaudière.

Mots-clés: Chaudière, paille, monoxyde de carbone, oxygène, particules, température, gas efflux, efficacité

Introduction

The world energy consumption is predicted to grow by 56% between 2010 and 2040, and in this context EU made a 20-20-20 commitment for objectives to achieve in 2020 of reducing at least 20% of greenhouse emissions, increasing the share of renewable energies to 20% and diminishing energy consumption by 20% by improving efficiency. Following the EU strategy, in 2012 about 50% of the electrical energy in Portugal derived from RE and about 25% of the total energy consumed in that year was generated from endogenous sources. In 2010, Portugal ranked as the fourth European country in Europe, surpassed by Sweden, Finland and Austria, in fulfilling the goals established by EU for the integration of renewable energies in final energy consumption. Nowadays some countries like Denmark has objectives as ambitious as reaching 2050 with an entire energy supply of 100% obtained from renewable energies. In Denmark in 2015, according to the EU calculation method, 30% of energy consumption was from renewable energy. The production of electricity based on renewable energy accounted for 56.0% of the electricity supply. Of this, wind power contributed with 41.8%. Biomass was 11.0% (DANISH ENERGY AGENCY, 2015). One possibility that can contribute for achieving a carbon light economy is the use of cereals straw as a biomass feedstock. Indeed, like with any other kind biomass, the possibility of using straw as a fuel is mainly due to its CO_2 neutrality. Cereal straw has a huge potential in Europe for generation of bioenergy. In Portugal wheat straw has an estimated energy of 5.4PJoules (AVELAR *et al.*, 2005) or 277.7GWh from an estimated area of 227270ha in 2000. This is a small occupation area comparatively, e.g., with Denmark, which is a country where straw is a high relevant kind of biomass. Indeed Denmark, with a total area of an order of half magnitude of Portugal, shows an actual cereal occupation of 1.55million ha (GYLLING *et al.*, 2016) and a total amount of straw of about 6 million tons. An average grain yield in Portugal can be estimated as 4400kgha^{-1} comparing with Denmark's 5916kgha^{-1}. A country like UK, with a total area about 2.5 times that of Portugal, has a wheat area of about 1.8 thousand hectares, with a total annual straw yield of about 6.4 million tons. Estimations for cereals straw in Portugal are of about 500ktonsyear^{-1} (e.g., SOUSA, 2009).

Straw yield can reach up to 40% yield relatively to grain and data for Canada, point to a ratio straw/grain of 1.5 (MORISSETTE *et al.*, 2013). Of the total straw production only a minor part is used for energy, with the major part are allocated to agricultural purposes such as animal feeding. A part of the straw is not collected, but is chopped and plowed down after the harvest. The main components of cereal straws are cellulose (40%-50%), hemicelluloses (20%-40%), lignin, (15%-20%) and extractives (5%-10%). Woody biomass has generally a higher lignin and lower hemicelluloses content (DODSON, 2011).Straw used as a fuel has a 14-20% moisture content, and amounts of carbon lower than 50%, 6% of hydrogen, 42% of oxygen and smaller amounts of nitrogen, sulfur, silicon and other chemical elements such as Na, K and Cl (e.g., NIELSEN *et al.*, 1998). The high heating value of wheat straw ranges from 16.2MJ/kg to 17.4MJ/kg. The optimal moisture content for burning is 14-20% although some boilers cope with a maximum of 65%. The bulk density of baled straw is 50-150 kgm^{-3}, much lower than e.g. a bituminous coal with 800-900kgm^{-3}. The densification of straw through pelletizing, for example, allows achieving mass weight of 500-1000kgm^{-3}that, although at a higher production cost, facilitates the transportation and handling of biomass (DODSON, 2011).

Ash content of straws, like that of any of other agricultural residues, is highly variable, depending on fertilization, soil type or irrigation practices, and occur in higher amounts comparatively with woody biomasses (4% vs. 0.6% - 1.5%) (DODSON, 2011). This leads to fouling and slagging problems in burning facilities. In this particular, the emission of particles is highly dependent on the amounts of potassium, chlorine and silica on the feedstock, and a tenfold difference in the particles emission might occur for the same boiler with different straws, even under a high combustion quality with low CO emissions. This fact is reflected, for example, on the results of VERMA *et al.* 2011a, comparing particle emissions from combustion of pellets of five different agricultural and forest biomasses. On the other hand, the results available allow concluding that each type of combustion device has a characteristic course of the carbon monoxide emissions (BRADNA *et al.*, 2016). Typical theoretical straw burning occurs in four phases: phase 1 concerns free water vaporization; phase 2 consists on an initial pyrolysis burning with insufficient oxygen supply for the huge amount of biomass on a pilot or industrial scale (hundreds of kilograms) with the releasing of incomplete oxidized gases such as CO, CH_4, H_2, or other volatile organic compounds; phase 3 occurs with steady and sufficient oxygen flow, enough to burn steadily non-oxidized gases formed on phase 2 and biomass feedstock, giving water and CO_2 gases and a solid charcoal deposit after complete oxidation; finally phase 4 consists in residual charcoal burning with formation of additional carbon dioxide and ashes. For the full proceeding of this sequence, excess air should be provided to the boiler, and the ratio between the air supplied and the air required for a throughout combustion is the excess air ratio (λ ratio). The lambda probes located in the exhaust flue gases controls that ratio and, if needed, signals the control unit to supply an additional flow of secondary air. The major proportion of combustion heat is absorbed by the water in pipes in the boiler walls, while the remnant is vented as hot flue gas consisting in a mix of gaseous components such as CO_2, water vapor, other gases resulting from incomplete combustion and particles from ash or alkaline salts. The existence of alkali and chlorine in flue gas, give rise to sodium chlorine and potassium chlorine, compounds which are extremely corrosive for steel parts (e.g., tubes) in the boilers (e.g., NIELSEN *et al*., 1998).

In agriculture, straw heating facilities can be used for heating facilities e.g. of livestock, stables and grain drying plants. Today, many efficient straw burners with power ranging from 35 to 5000 kW are commercially available, mainly manufactured in Europe (MORISSETTE *et al*., 2013). The use of crop residues as a solid fuel for heating can be implemented with existing technology on a small scale, as long as exhaust air quality is well controlled. In Denmark, firing with straw in agriculture has been common practice in the last forty years. Along that period, the boiler technology was conspicuously improved as environmental priorities arose, concerning greenhouse gas, carbon monoxide and particle atmospheric emissions. In this context, Danish authorities institutionalized a public financial support for purchasing and test submission of boilers for straw, wood and grain. Under this scheme, the financial support would increase with the compliance of boiler equipments to environmental standards and high efficiency. The greatest technological improvements were made on the burning efficiency of batch-fired boilers, lowering the amounts of CO emissions, with heat nominal powers in the range of 50-500 kW.

The basic conditions to assure good combustion with lower emissions are the atmospheric turbulence and temperature in the burning environment (boiler) and an enough time of residence, of the order of a few seconds, of hot combustion gases in the environment. The significant minimizing of particle emissions, which, as mentioned above is highly dependent on input straw, has been achieved with the development of devices like electrostatic precipitators which can reach efficiencies as high as 98% (KRISTENSEN *et al*., 2016). The efficiency of combustion operation can be improved by supplying air in several stages (primary and secondary air) or by devices (economizers) allowing to heat water from the heat contained in emitted flue gases. Application of dust, recovered from straw combustion, in agricultural soils is a practical possibility that would avoid atmospheric emissions and would prevent a significant loss of nutrients and also contribute to restoration of soil fertility (DODSON *et al*., 2011; BRADNA *et al*., 2016).

The weight yield of straw from a wheat field can be of the order of 50%. In Denmark, a country where, as aforementioned, straw is a major biomass source, the most widely used cereal is winter wheat followed by spring barley. About 15% of the cereal area is rye and oats. In general wheat straw has higher ash content than woody biomass (4% vs. 0.6-1.5%) and a HHV of the same order in magnitude. The alkali content is much higher in the herbaceous raw materials compared to woody and coal stuffs. Like other biomasses straw is carbon neutral, with a level of net zero carbon dioxide emissions usually considered.

In this whole context, the objectives of this work were the evaluation of: i) combustion dynamics on a pilot scale batch boiler of two 200 kg batches of wheat straw, concerning variables of the flow gas, continuously monitored; ii) energy balance of the process and iii) particle and carbon monoxide emissions.

Materials and methods

Two experimental trials of combustion of 200kg wheat straw batches were performed in April 3 and April 4 of 2017, respectively, (Figure 1) in a combustion pilot scale laboratory at the Foulum campus of Aarhus University in Denmark, according to the experimental proceedings established in that facility (KRISTENSEN and KRISTENSEN, 2004). The two experiments lasted 344mins and 315mins, respectively. An electronic platform scale was used for weighing the amount of fuel used in each test. A tractor with front loader was used to feed the straw bale into the burning chamber. Straw moisture was calculated by drying a 200g straw sample at 105ºC till constant weight. Ash content was measured by burning a 200g straw sample in a muffler at 550ºC during 3 hours.

The boiler used for burning the straw was a cubic combustion chamber of 2.5m^3, Alcon, model 1220 BA, with 125kW of nominal power and insulating stones covering most of surface of walls and roof. The temperature and energy monitoring inside the boiler were done with a PT100 sensor, Kamstrup, Model Multical 402. Also laboratorial and pilot weighing machines were of trade mark Kern, Model ABJ 120 – 4NM and Scanvaegt Model SC500. The data are measured, stored and averaged in every minute with a CR1000 datalogger. The carbon monoxide emissions with were measured with an infra-red gas analyzer ABB, Model EL3020 Uras 26, and the O_2 content on the flue gas were measured with an ABB, Model EL 3020 Magnos 26 analyzer (Figure 2).

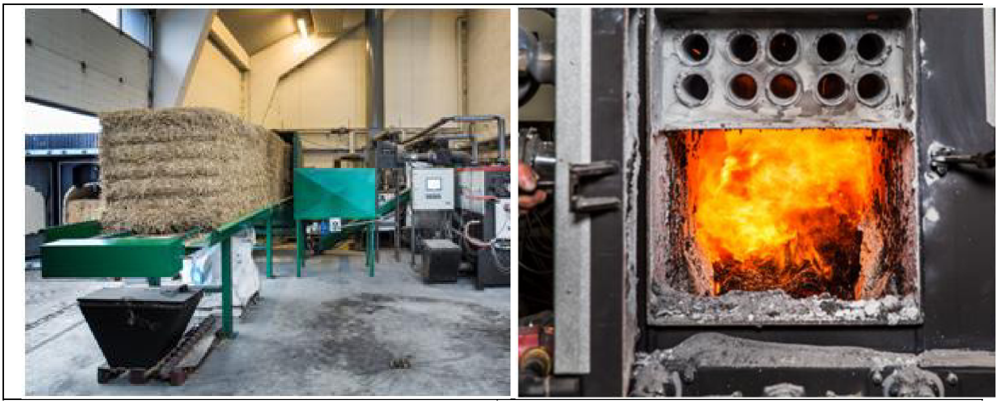


Figure 1 - Combustion equipment: feeding 200 Kg straw bale (right) and burning in the boiler (left)

Figure 2 - Gas analyzers (left) and data acquisition (right)

The content of particles of the flue gas was measured with a probe located in the center of the flue gas exhaust tube. Velocity and volume of flue gas is measured prior to the sampling with a pitot tube, and the velocity of the air sample taken out by the probe is adjusted to be the same as the velocity of the flue gas in the exhaust tube (isokinetic suction). About 1% of the flue gas is sampled by the probe and lead to a filter which after a fixed time (minimum half an hour) is weighed. The burning trials lasted for about 5 hours, until an amount of O_2 in the flue gas exceed 18%. Measurements of particle emissions were made at six moments, only at the April 3 experiment. The air supplied to straw burning was split up in two flows of primary air and secondary air, through the monitoring of a lambda sensor mentioned above. Primary air was injected from the top of chamber through two nozzles and secondary air was spread from a nozzle in the back wall (Figure 3)The nozzles are equipped with propeller swirls which increase the turbulence of air supplied and thereby the efficiency of straw combustion. The flue gas is cooled by convection and conductive heating of water circulating in a network of 30-50 tubes in the chamber walls, with turbulence devices aiming to cooling rate of flue gases. The thermal energy from burning one straw bale is recovered by heating water and storing it in a water tank above the chamber. The accumulated ash in the chamber floor was removed by using a tractor with an ash scoop fitted in the front loader.

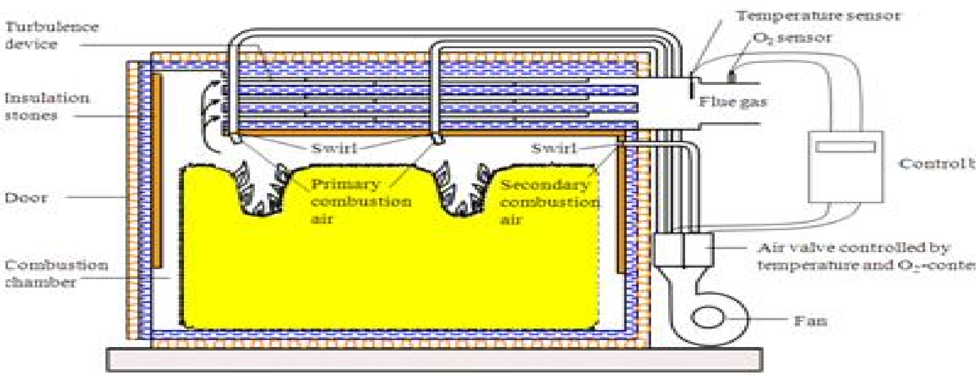


Figure 3 - Diagrammatic representation of the straw boiler and burning

Results and discussion

Two cubic wheat straw samples of 200Kg with 13% moisture content and 3% ash content were used in the two trials. The ash and moisture were determined gravimetrically and their values allowed obtaining an average HHV of

4.19kWh/Kg of biomass according to the following empirical expression, obtained through pilot lab correlations (KRISTENSEN and KRISTENSEN, 2004):

$$HHV = 18.4 - 0.2(m_w + ash) \quad \text{Equation 1}$$

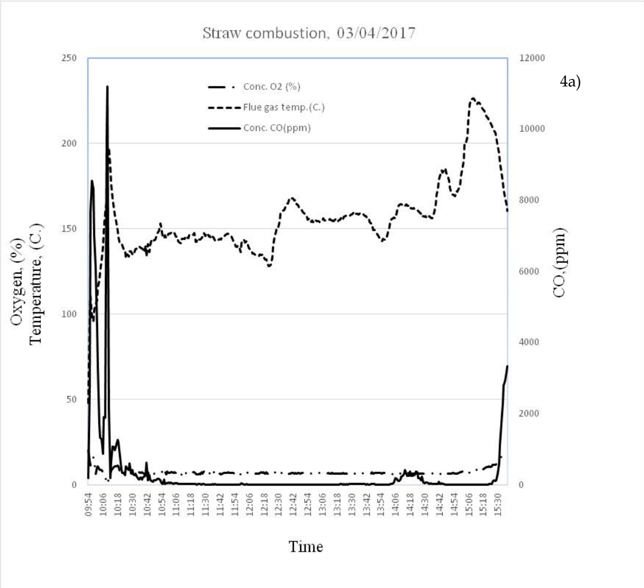
where HHV is the high heating value (MJ/kg), m_w and ash are the moisture and ash contents (%) on a wet basis. The estimated average energetic efficiency of this pilot operation was 83.3%, considering an energy content of 840kWh in both trials, for the 200Kg wheat straw batches and a measured value of 700kWh for heat exchanged on water heating. This efficiency compares well with an energetic efficiency of 68% obtained with burning of wheat straw in a 176kW boiler for agricultural purposes (MORISSETTE *et al.*, 2013) or with data of wood pellets combustion, ranging between 85% and 93% for a set of five boilers with nominal powers ranging between 15 kW and 40 kW (VERMA *et al.*, 2001b).

Essentially, the evolution of straw biomass in the experiments was mainly dependent on the dynamics of the geometry of the straw bale in the chamber with the proceeding of the combustion. The main parameter to be controlled was oxygen concentration in the flue gas, which is directly linked to flue gas temperature and oppositely associated with the carbon monoxide in this gas. The variation of flows in primary and secondary air, automatically triggered by lambda probe and the flue gas analyzers, assured the monitoring of gas concentrations and thereby in flue gas temperature. The total measured volume of flue gas from the boiler was of about 500m^3 per hour. Specifically, the secondary air inflow is automatically triggered when oxygen concentration in flow gas is lower than 8%. The overall time evolution of April 3 trial in is depicted in Figure 4. Figure 5 shows the evolution of that trial by parting the interval 9h54m-15h38m in three blocks. Indeed we can establish a first stage of straw combustion in April 3 in the period between 9h54m and 10h40m (Figure 5a) wherein initial strong biomass combustion on the bale surface led to a drop in oxygen concentration in flue gas to a minimum of 0.5% and peaks of CO concentration and flue gas temperature of 11200ppm (Figure 4) and 198ºC, respectively. Largest CO emission concentrations during ignition or extinguishing of the combustion process are reported by FIEDLER and PERSSON, 2009. Thereby an additional supply of secondary air was imposed to stabilize the oxygen and carbon monoxide concentrations to about 7.5% and 400 ppm so that the average oxygen and CO concentrations in flue gas in this period (9h54m to 10h40m) were 8% and 2000ppm, respectively. The average flue gas temperature was also abated in this period to 140ºC. A second period occurred between 10h40m and 15h, (Figure 5b) wherein the patterns of oxygen concentration and flow gas temperature were steady with an average of 6.75%

of oxygen concentration and an average flue gas temperature of 153ºC. In this period the bulk of the straw bale was burned and a slight oscillatory patterns of in flue gas oxygen concentration and temperature, can be due certainly to small changes in bale structure allowing to slight differential patterns of flame distribution, which were, of course, monitored to gas analyzers, trigging thereby minor changes in supply in primary and secondary air. Finally, when the upper-half of the straw bale was burned, a third stage on the combustion could be evaluated from 15h till the end of the combustion process at 15h38m (Figure 5c). At this later stage the access of primary air was of maximum, due the emptier space, while the feeding of secondary air was closed. The main features registered were the peaking of flue gas temperature to temperatures as high as 226ºC, and of the oxygen concentration as well to levels above 10%, excessive because the straw was overly incinerated. A collapse of the bale induced a partial smothering of the adjacent atmosphere with an episodic increase of CO emissions up to 3000ppm (Figure 4). The combustion was assumed as finished when the oxygen content in the flue gas exceeded 18%. The average CO and O_2 concentrations in flue gas, in the whole experiment, were 365ppm and 7.4%, respectively. The correspondent average flue gas temperature was 156ºC.

In the April 3 trial a isokinetic sampling of particle emissions in the flue gas in six periods on the trial: 1- 9h57m till 10h45m, 2- 10h58m till 11h50m, 3- 11h58m till 12h50m, 4- 12h57m till 13h50m, 5- 13h58m till 14h52m and 6- 14h57m till 15h38m. The average volume of gas sampled was 0.403m^3 and the average emission of particles was 455$mgnm^{-3}$(considering an oxygen amount of 10%), well above the threshold of 60$mgnm^{-3}$ required by environmental protection standards for batch fired straw boilers. The threshold value will be applied from January 2018 and achieved through the application of electrostatic precipitators (KRISTENSEN *et al.*, 2016) under the European standard EN 303-5. The particle emissions achieved in this work compare with emissions reported from combustion with other agricultural residues such as sunflower husk pellets (VERMA *et al.*, 2011a) (500 $mgnm^{-3}$) with a 40 kW boiler.

But the values of particle emissions of this work are high comparatively to the emissions, bellow 30 $mgnm^{-3}$ of wood pellets combustion, concerning the aforementioned study (VERMA *et al.*, 2001b).



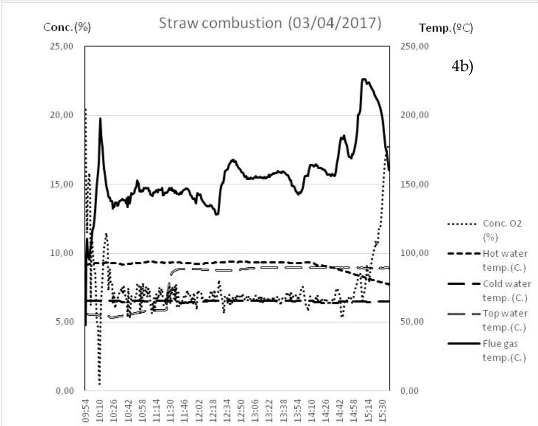


Figure 4 – Time evolution of straw combustion in 3 the April trial. Figure 4a) depicts the time variation of 3 variables in flue gas (concentrations of O_2, CO and temperature). Figure 4b) depicts the time variation of the same gases plus the cold and heated water and the temperature of the water in the top of the storage tank

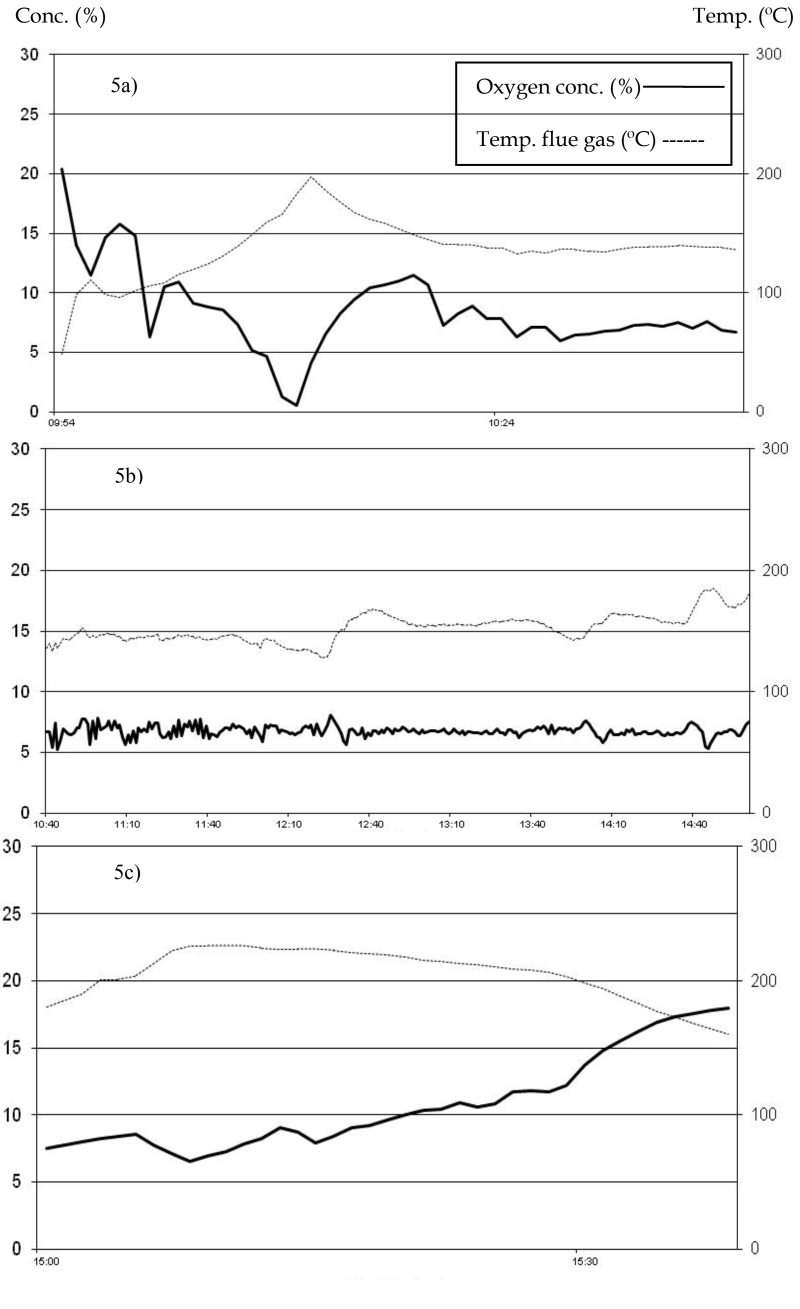


Figure 5 – Evolution of straw burning in April 3 trial. Figures 5a), 5b) and 5c), concern to time periods 9h54m-10h40m, 10h40m-15h and 15h-15h38m, respectively*)*

A similar overall pattern of combustion could be registered for the combustion trial of April 4 (Figure 6) occurring from 9h58m till 14h13m. Here an initial period between 9h58m and 10h25m (Figure 7a) was characterized by a strong combustion wherein oxygen concentration in flue gas decreased from 20.8% to values as low as 5.6%, the concentration in carbon monoxide peaked to values of the order of 1780ppm and the flue gas temperature reached 170ºC. A supplement in secondary air flow stabilized the concentration of oxygen to about 7.1%, flue gas temperature to 164ºC and carbon monoxide concentration to about 30-60ppm. The average value of oxygen concentration in flue gas for this period was 8.1%, and the correspondent values for flue gas temperature and carbon monoxide concentration were 163.2ºC and 312ppm. A second period between 10h25m and 12h10m (Figure 7b) was characterized by a steady burning of the straw bale with average values of 6.9% of oxygen concentration, 159ºC for flue gas and 9ppm for carbon monoxide concentration. A third period, between 12h10m and 13h00m (Figures 6 and 7c) was characterized by an unsteady combustion, reflected by the oscillatory pattern of oxygen concentration between 6 and 8% and of flue gas temperature between 150ºC and 230ºC. Carbon monoxide concentration also showed episodic peaks of 151ppm and 249ppm at 12h52m and 12h53m, respectively. This behavior is a consequence of uneven spatial pattern burning on the boiler, with higher incinerated parts mixed with less incinerated ones, inducing an unsteady airflow and allowing to some increasing of secondary airflow in order to increase the combustion rate of partially incinerated areas of the bale with the increasing of oxygen concentration and the reducing of same CO emission. The average rates of oxygen concentration for this third period was 7.12%, 195ºC for the flue gas temperature and 8 ppm for carbon monoxide concentration in the flue gas. Finally the latter full blown combustion of the remaining residue of non or partially burned straw lasted from 13h to 14h13m (Figure 7d) a high average temperature (210ºC) for flue gas, and increasing concentration of oxygen till 18% (ending of process) with a 8.73% average on this period. As in the April 3 trial, a small peak of CO emission of 1400 ppm in the end of the experiment occurred. The episodic increase of carbon monoxide emissions in the end of the two experiments is perhaps due to a high amount of air in the boiler which cooling the combustion chamber and decreasing the combustion rate, with higher emission of carbon monoxide (BRADNA *et al*., 2016).

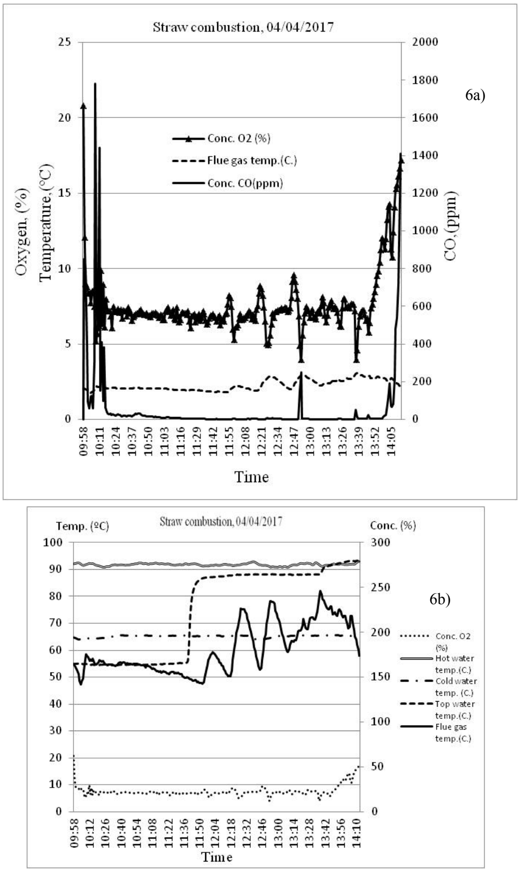


Figure 6 - Time evolution of straw combustion in 4 April trial. Figure 6a) depicts the time variation of 3 variables in flue gas (concentrations of O_2, CO and temperature). Figure 6b) depicts the time variation of oxygen concentration, cold and heated water temperatures and the temperature of the water in the top of storage tank

The average CO and O_2 concentrations in flue gas, in the whole experiment, were 58ppm and 7.6%, respectively. The correspondent average flue gas temperature was 181ºC. The emissions of CO in the two experiments were very low (as it can be seen in Figures 4a and 6a) at most minutes. This is particularly true in the experiment of April 4, wherein 227 CO minute records corresponded to CO emissions lower than 70 ppm, v.s. 28 higher than this threshold. In the data of the April 3 experiment the correspondent numbers were 241 and 105.

The steady decrease in the combustion CO emissions in this kind of boiler had been reported. For example from 1995 till 2002 typical emissions of CO decreased from 5000ppm to less than 1000ppm. These emissions are well within the thresholds imposed by the European standard EN 303-5 for heating boilers with solid fuels from the European Committee for Standardization (CEN) (EN 303-5. 2012).

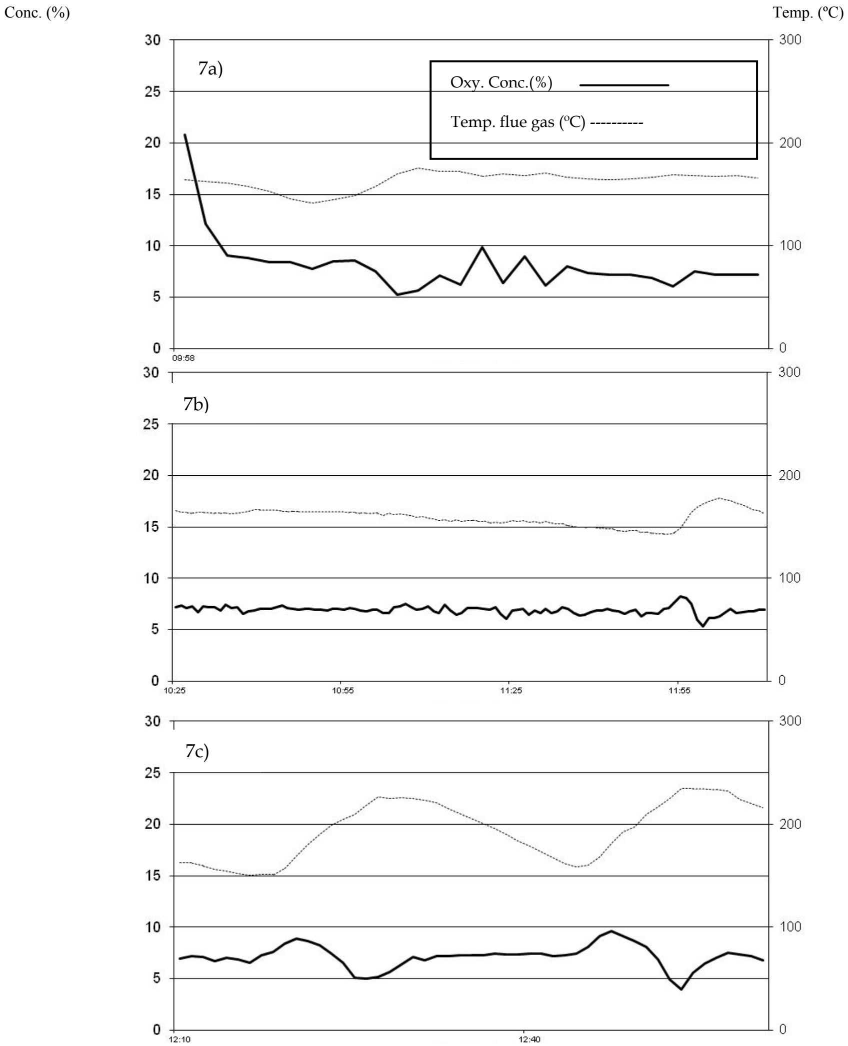


Figure 7 – Evolution of combustion process in April 4. Figures 7a), 7b) and 7c), concern to time periods 9h58m-10h25m, 10h25m-12h10m and 12h10m-13h00m, respectively

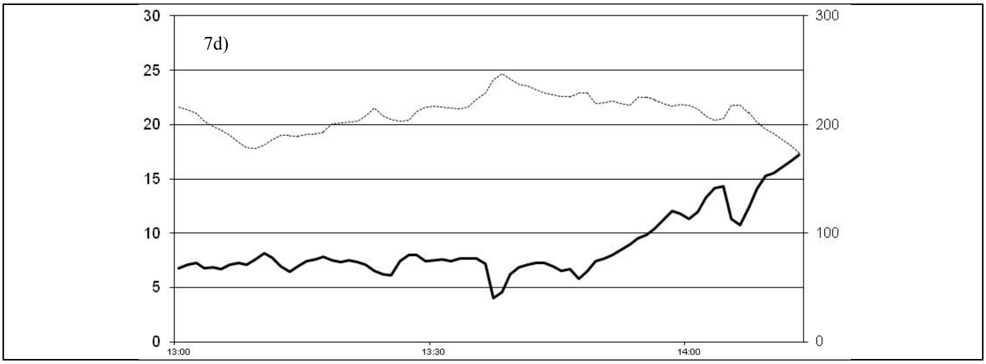


Figure 7 – (continuation); Figure 7d) concern the period 13h-14h13m

The average values of CO emissions obtained in this work are of the same order of magnitude from these obtained from wheat straw combustion from a boiler with a much lower nominal power (18kW) in Czech Republic (average CO emissions of 1040.64 mgm^{-3}) (BRADNA *et al.*, 2016). Our CO emission results compare also with data of the same order of magnitude from wood pellet combustion in residential boilers (VERMA *et al.*, 2011b) (100ppm) CO emissions from combustion of other agricultural residues such as woody biomass, tomato seeds and skin residues (1800ppm) (GONZÁLEZ *et al.*, 2004), sorghum (2500ppm) (GONZÁLEZ *et al.*, 2006) or citrus pectin waste (VERMA *et al.*, 2011a), (800ppm). The data of carbon monoxide emission of this work are also much lower with these from burning wheat straw in a boiler with higher nominal power (175kW) of around 2210 mgm^{-3}(MORISSETTE *et al.*, 2013).

The heat released by the combustion was used in water heating in the storage tank from a quasi steady temperature of 64ºC to a steady temperature of 92ºC in the top of the tank (Figures 4b and 6b), indicated in the top water lines for the April 3 and April 4 trials, respectively. The average flow of water was 12.12m^3h^{-1}. The hot water heated from the combustion was delivered to an accumulation tank. Fig. 4b) and 6b) show the time evolution of the top water in this accumulation tank. In both trials of April 3 and April 4, it can be seen that the top water temperature in the accumulation tank, at about one half of the total period, increased from one stationary level of about 55ºC to another of 89ºC due to the constant inflow of hot water from the combustion.

Conclusions

The straw boiler optimized design used in this experiment allowed controlling the primary and secondary air flow, so that the energetic efficiency of burning was high (83.3%) and the harmful emissions of carbon monoxide were reasonable with averages of 365ppm and 58ppm in the two trials performed. Also the particle emissions averaging 516mgnm^{-3} were reasonable and can be significantly reduced with the application of a device such as and electrostatic precipitator which can reach dust collection efficiencies as high as 99%. These good results are enhanced given the pilot scale dimension of the boiler with high dimension (2.5m^{3}) and relatively high nominal power (125 kW), comparatively to pellet boilers usually used. On the other hand, dust recovered from straw combustion could be beneficially applied to agricultural soils, effectively recycling nutrients and minimize resources allocation to industrial fertilization facilities and optimizing the sustainability of energy production from biomass.

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Entregue para publicação em junho de 2017
Aceite para publicação em junho de 2017

Silva Lusitana, **25**(1): 51- 77, 2017

Propagation of Nine Endemic Plant Species from Madeira Island (Portugal)

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Abstract. Efficient propagation of endangered plant species is a critical factor in successful ecological restoration and conscientious habitat management. Hence, propagation trials of nine endemic plant species of Madeira (*Anthyllis lemanniana* Lowe, *Armeria maderensis* Lowe, *Cedronella canariensis* (L.) Webb & Berthel., *Erica maderensis* (Benth.) Bornm., *Genista tenera* (Jacq. ex Murray) Kuntze, *Helichrysum melaleucum* Rchb. ex Holl, *Pericallis aurita* (L'Her.) B. Nord., *Sideritis candicans* Aiton and *Teline maderensis* Webb & Berthel.) were carried out. Plant propagation requirements and their sexual and vegetative propagation methods were studied. Seed germination success varied between species. Germination rate exceeded 70% in six out of nine species, being lower than 30% in *Pericallis aurita,* while *H. melaleucum* seeds did not germinate. Vegetative propagation yielded lower success rates, with three species (*Erica maderensis*, *Genista tenera* and *Teline maderensis*) unable to establish roots, and three species (*Helichrysum melaleucum*, *Pericallis aurita* and *Sideritis candicans*) exceeding 60% of the rooting success.

Establishment of the propagation requirements of these species could be regarded an important tool for supporting Madeira’s flora conservation programs.
Key words: Seed propagation, vegetative propagation, plant conservation

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Propagação de nove espécies de plantas endémicas da ilha da Madeira (Portugal)
Sumário. A propagação eficaz de espécies de plantas ameaçadas pode ser um fator crítico numa restauração ecológica de sucesso e numa gestão consciente de habitats.
Por conseguinte, foram realizadas ensaios de propagação de nove espécies de plantas endémicas da Madeira (*Anthyllis lemanniana* Lowe, *Armeria maderensis* Lowe, *Cedronella canariensis* (L.) Webb & Berthel., *Erica maderensis* (Benth.) Bornm., *Genista tenera* (Jacq. Ex Murray) Kuntze, *Helichrysum melaleucum* Rchb. Ex Holl, *Pericallis aurita* (L'Her.) B. Nord., *Sideritis candicans* Aiton e *Teline maderensis* Webb & Berthel.).

Foram analisados os requisitos de propagação destas espécies através de métodos de propagação sexual e vegetativa.

O sucesso da germinação das sementes variou entre as espécies. A taxa de germinação foi superior a 70% em seis das nove espécies, sendo inferior a 30% em *Pericallis aurita*, e de 0% para *H. melaleucum*. A propagação vegetativa apresentou taxas de sucesso inferiores, com três espécies (*Erica maderensis*, *Genista tenera* e *Teline maderensis*) incapazes de estabelecer raízes. Por outro lado, três espécies apresentaram taxas de enraizamento superiores a 60% (*Helichrysum melaleucum*, *Pericallis aurita* e *Sideritis candicans*).

O estabelecimento dos requisitos de propagação dessas espécies pode ser considerado como uma ferramenta importante na conservação da flora da Madeira.
Palavras-chave: Propagação de sementes, propagação vegetativa, conservação de plantas

Propagation des neuf espèces de plantes endémiques de l'île de Madère (Portugal)
Résumé. La propagation efficace des espèces végétales menacées est un facteur critique pour la restauration écologique réussie et la gestion consciencieuse de l'habitat.

Ainsi, ont été réalisés les essais de propagation de neuf espèces de plantes endémiques de Madère (*Anthyllis lemanniana* Lowe, *Armeria maderensis* Lowe, *Cedronella canariensis* (L.) Webb et Berthel., *Erica maderensis* (Benth.) Bornm., *Genista tenera* (Jacq. Ex Murray) Kuntze, *Helichrysum melaleucum* Rchb. Ex Holl, *Pericallis aurita* (L'Her.) B. Nord., *Sideritis candicans* Aiton et *Teline maderensis* Webb & Berthel.).

Les besoins de propagation des plantes et leurs méthodes de propagation sexuelle et végétative ont été étudiés.

Le succès de la germination des semences variait d'une espèce à l'autre. Le taux de germination a dépassé 70% chez six espèces sur neuf, soit moins de 30% chez *Pericallis aurita*, alors que les graines de *H. melaleucum* n'ont pas germé.

La multiplication végétative a donné des résultats inférieurs avec trois espèces (*Erica maderensis*, *Genista tenera* et *Teline maderensis*) incapables d'établir des racines, alors que trois espèces (*Helichrysum melaleucum*, *Pericallis aurita* et *Sideritis candicans*) excédant 60% du succès d'enracinement.

L'établissement des besoins de propagation de ces espèces pourrait être considéré comme un outil important pour soutenir les programmes de conservation de la flore de Madère.
Mots-clés: Propagation de semences, multiplication végétative, conservation des plantes

Introduction

Oceanic islands tend to have unique floras, with higher number of endemisms, with the Archipelagos of Madeira and Selvagens being a prime example. Their flora comprises of 1,204 vascular plant species, 780 native and 154 endemics, with endemism representing 13% of the overall diversity (JARDIM & SEQUEIRA, 2008). Madeira Island has the second richest flora of Macaronesia, harboring the highest biodiversity *per* area (BORGES *et al*., 2008).

Undoubtedly, Madeira is included in one of Europe's hotspots of biodiversity, being integrated in the biodiversity hotspot of the Mediterranean (MYERS *et al*., 2000; BORGES *et al*., 2008), and a recognized site for conservation priorities (BORGES *et al*., 2008; BILZ *et al*., 2011). Many plant species have small population sizes or are threatened and, therefore, there is a need for *ex situ* and *in situ* conservation efforts in order to safeguard this unique natural heritage.

The effects of climate changes and anthropogenic activities on native ecosystems are also affecting Madeira. Over the last years we have noticed some vulnerability of Madeira's plant cover concerning forest fires and floods. Historical climatic records have shown a progressive climate warming throughout the last century, reaching up to 0.51°C per decade in some areas, and it is expected to increase in the decades to follow (MIRANDA *et al*., 2006; SAUTER *et al*., 2013). A considerable reduction in annual precipitation (up to 30%) (MIRANDA *et al*., 2006; CRUZ *et al*., 2009; SAUTER *et al*., 2013) and water availability (up to 40-50%) (OLIVEIRA *et al*., 2006) are also predicted. These constrains will have a critical impact on water resources of small creeks and ground water aquifers, threatening natural ecosystems (SAUTER *et al*., 2013). The expected changes will lead to the expansion of invasive species, an altitudinal shift in the native vegetation that will undergo a decrease in its suitable area (FREITAS & COUTINHO, 2006; CRUZ *et al*., 2009), and an expected increase of plant disease and pests (CORREIA *et al*., 2006).

Consequently, under these conditions, mountain ecosystems and their vegetation will suffer an increasing pressure. The actions to restore these fragile ecosystems will be of great importance to reverse the trend of species loss (DORNER, 2002). The use of native species is advantageous to successful ecosystem restoration. Native plants form self-sustaining, locally adapted communities that do not require great maintenance efforts, and hence tend to resist damage from numerous external stress factors, such as fires, drought and diseases (DORNER, 2002).

The nine plant species studied in this work (*Anthyllis lemanniana* Lowe, *Armeria maderensis* Lowe, *Cedronella canariensis* (L.) Webb & Berthel., *Erica maderensis* (Benth.) Bornm., *Genista tenera* (Jacq. ex Murray) Kuntze, *Helichrysum melaleucum* Rchb. ex Holl, *Pericallis aurita* (L'Her.) B. Nord., *Sideritis candicans* Aiton and *Teline maderensis* Webb & Berthel.) are prime examples of native plant species that should be used in the ecological restoration of these ecosystems as they represent a succession stage that leads to the climax stage of the target habitat (CAPELO *et al*., 2004). They represent the understory and edges of the Laurel and Heaths forests (CAPELO *et al*., 2004), and are expected to be successful colonizers after a habitat disturbance.

Although seed propagation is a preferred method for habitat restoration or plant recovery purposes due to genetic diversity conservation (BONNER & KARRFALT, 2008), low seed availability favors vegetative propagation as a faster alternative and an efficient method for the multiplication of some species.

Furthermore, the seeds of many native wild species require specific conditions to germinate (MEYER, 2006), resulting from their adaptation to ecological and environmental cues that trigger germination (LUNA *et al*., 2009). This is due to seed dormancy mechanisms developed in nature to increase the chances of seedling survival by preventing germination during unsuitable ecological conditions or by delaying germination (MEYER, 2006; BONNER & KARRFALT, 2008; TAIZ & ZEIGER, 2010).

A variety of treatments can be used to break dormancy, including scarification (mechanical or chemical), soaking, light, germination stimulators (such as gibberellins, GA) and stratification (or chilling) (BONNER & KARRFALT, 2008; LUNA *et al*., 2009; HARTMANN *et al*., 2011).

When seed germination is unsuccessful, vegetative propagation by rooted cuttings, air layering, grafting, budding or micropropagation could be attempted as alternative methods of plant propagation (BONNER & KARRFALT, 2008). Some plant species, including those in wild habitats, develop vegetative reproduction as an alternative way of reproduction. According to the best of our knowledge, information about seed germination success and vegetative propagation of these nine species has not been published to date.

The main objective of this study was to attain the know-how on the propagation requirements of the nine target plant species and establish propagation protocols considering both the seed and vegetative methods. Furthermore, the study of their propagation may assist in the conservation of these *taxa,* from which three species face the risk of extinction (or are vulnerable) and have low population counts (*A. lemanniana, A. maderensis* and *S. candicans*)

(JARDIM *et al*., 2006), and two of which are on the list of the 100 taxa for priority management in Madeira (*A. lemanniana, A. maderensis*) (FARIA *et al*., 2008). Additionally, *A. lemanniana* is listed in the Bern Convention and Habitats Directive (Annexes II, IV) (JARDIM & SEQUEIRA, 2008; BILZ *et al*., 2011). Moreover, the species studied in this work are part of protected habitats, namely the "Endemic Macaronesian Heaths" and "Macaronesian laurel forests (*Laurus, Ocotea*)", both priority habitats (EUROPEAN COMMISSION, 2013).

Materials and Methods

Plant material

The reproductive features of nine species belonging to five families were studied: *A. lemanniana*, *G. tenera* and *T. maderensis* from Fabaceae; *C. canariensis* and *S. candicans* (Lamiaceae); *H. melaleucum* and *P. aurita* (Asteraceae); *A. maderensis* (Plumbaginaceae); and *E. maderensis* (Ericaceae) (Table 1).

Plant material was collected from 18 wild populations, located along different altitudinal ranges. On the south face of the island, the collection sites were Assomada (*c.* 200 m a.s.l.), the Ecological Park of Funchal (*c.* 470 m a.s.l.), Monte da Tabaiba (*c.* 272 m a.s.l), near Poiso (*c.* 1,414 m a.s.l), Encumeada (800 – 900 m a.s.l.), Levada da Serra do Faial (750 – 800 m a.s.l.) and Ribeiro Frio (830 – 860 m a.s.l). On the north face, the surveyed sites included Folhadal (1,000 m a.s.l.), Funduras (*c.* 597 m a.s.l), Portela (*c.* 626 m a.s.l), Achadas da Cruz (575 m a.s.l.), Levada da Ribeira da Janela (430 – 460 m a.s.l.), Chão da Ribeira (*c.* 500 m a.s.l.), Levada dos Cedros (840 – 1,130 m a.s.l), Lombo do Mouro (*c.* 1,280 m a.s.l). Additionally, several sites cross through the island, encompassing both the north and south faces, including the Central Mountain Massif, namely Caminho Real da Encumeada (*c.* 940 m a.s.l.), Paúl da Serra (*c.* 1,500 m a.s.l) and the Vereda do Arieiro (1,542 – 1,818 m a.s.l).

In general, plants grown at the collection sites bloom and set fruits from spring through autumn, depending, however, on climatic conditions (PRESS & SHORT, 1994; JARDIM & FRANCISCO, 2000). In most cases, vegetative plant material was collected between May and November 2011 and seeds were collected from June through November 2011.

Table 1 – Plants species studied, with description of their biological type, ecology and collection sites (PRESS & SHORT, 1994; JARDIM *et al.*, 2007)

Species (Family)	**Life Form Life cycle type**	**Ecology**	**Altitudinal range [m] a.s.l.**	**Site and Date of Seed collection**
• *Anthyllis lemanniana* (Fabaceae)	Decumbent to ascending, much–branched from base, herbaceous woody–based perennial. Polycarpic.	Cliffs, steep rocks and ledges in the mountainous central region of Madeira Island.	1,200 – 1,800 m	Pico do Arieiro, 08/2011
• *Armeria maderensis* (Plumbaginaceae)	Tufted herb with woody, branched stock. Monocarpic.	Exposed rocky and sandy sites on the summits of the high central peaks of Madeira Island.	Highest altitudes (*ca.* 1,800 m)	Pico do Arieiro, 07/2011, 08/2011
○*Cedronella canariensis* (Lamiaceae)	Perennial herb to small bush, woody at base. Polycarpic.	Laurisilva and shady sites of Madeira Island.	Above 500 m	Levada dos Cedros, 07/2011, 09/2011; Ribeiro Frio, 07/2011, 08/2011; Poiso, 07/2011; Ecological Park of Funchal, 07/2011; Lombo do Mouro; 08/2011; Encumeada, 08/2011, 09/2011
• *Erica maderensis* (Ericaceae)	Stocky shrub up to 80 cm, usually prostrate. Woody perennial. Polycarpic.	In heath sites and on bare rock faces in the mountainous central region of Madeira Island.	1,400 – 1,800 m	Only vegetative propagation
• *Genista tenera* (Jacq. ex Murray) Kuntze (Fabaceae)	Unarmed woody perennial shrub, up to 2,5 m. Polycarpic.	Exposed rocky cliffs and ravines, mainly on the south side.	From sea level up to 1,700 m	Caminho Real da Encumeada, 07/2011; Monte da Tabaiba, 07/2011; Assomada; 07/2011;
• *Helichrysum melaleucum* Rchb. ex Holl (Asteraceae)	Woody–based small shrub, perennial, up to 100 cm. Polycarpic.	Exposed rocky cliffs and steep rocks	From sea level up to 1,700 m	Achadas da Cruz, 08/2011
• *Pericallis aurita* (L'Her.) B. Nord. (Asteraceae)	Slender, open semi–hardwood perennial shrub up to 1.5 m. Polycarpic.	Laurisilva and ravines and on rocky slopes in the higher parts in the interior of Madeira Island.	Altitudes above 1,000 m.	Caminho Real da Encumeada, 07/2011; Encumeada, 07/2011; Funduras, 08/2011; Portela, 08/2011; Paúl da Serra, 08/2011; Achadas da Cruz, 08/2011
• *Sideritis candicans* Aiton (Lamiaceae)	Herbaceous small shrub, perennial, 45 – 100 cm. Polycarpic.	Laurisilva and clearings and open, sunny sites in Madeira Island.	600 – 1,700 m	Lombo do Mouro, 08/2011; Encumeada, 08/2011
• *Teline maderensis* Webb & Berthel. (Fabaceae)	Unarmed woody perennial evergreen shrubs or small tree, up to 6 m. Polycarpic.	Laurisilva and rocky wooded ravines, and maritime cliffs.	From sea level up to the highest altitudes	Encumeada, 08/2011; Levada da Ribeira da Janela, 08/2011; Ribeiro Frio, 11/2011

• Endemic to Madeira; ○Endemic to Macaronesia.

The seeds were air–dried in trays for a few days, and subsequently manually cleaned. Any visually malformed or immature seeds were rejected. The seeds were then stored in dry conditions at room temperature in glass containers with silica–gel. The vegetative material was propagated, at the most, a day after collection.

The study was conducted in a non-acclimatized greenhouse located at the Floriculture Centre (Lugar de Baixo, Ponta do Sol) on the southern coast of Madeira, 10 – 40 m a.s.l. The climate is dry infra-mediterranean, characterized by a long dry season during the summer months (MESQUITA *et al*., 2004). The greenhouse has a roof covered with hard plastic panels, and open walls covered with nets. The temperatures inside the structure ranged from 29°C (day) to 19°C (night) during summer/autumn, while in winter temperatures varied between 23-24°C (day) and 14-15°C (night).

Seven seed pre-treatments and three vegetative propagation methods were used to study their effects on seed germination and plant propagation.

Final germination percentage was calculated for seed propagation and the rooting percentage was reported for the vegetative propagation.

Statistical analysis for seed germination and vegetative propagation data analysis was performed using the SPSS Statistics 22 software package. Both parametric and nonparametric tests were performed, and the *p*-value (<0.05) was calculated to establish significant differences between each treatment. For statistical analysis, data as percentages were transformed to arcsine$\sqrt{}$ $(x/100)$.

Seed propagation trials

Germination trials were carried out between June 2011 and April 2012. In general, seven seed treatments were tested, namely: a) control, without treatment; b) mechanical scarification; c) cold water immersion; d) mechanical scarification, followed by immersion in water; e) gibberellic acid (GA_3) treatment; f) scarification in hot water; and g) scarification in boiling water (Table 2).

Due to limited seed availability, the above–mentioned treatments, including control tests, were selectively applied only to the species that were indicated as relevant in several bibliographical references. Specifically, control tests for *C. canariensis* and *T. maderensis* were not performed based on the seed hardness of this species that would turn the seed unable to imbibe water, and therefore, unable to germinate (HARTMANN *et al*., 2011). Similarly, prompted by the bibliographical references, control test were not performed on *A. lemanniana* (DOUSSI & THANOS, 1993, 1994; IBAÑES & PASSERA, 1997; PRIETO *et al.*, 2004; MORBIDONI *et al.*, 2008). The rarity of some species and scarcity of seed production affected the seed sample size, which was not uniform throughout the tests. Therefore, each trial contained a variable number of seeds according to the species, with 2 to 6 replicates (for more details see Table 2).

Table 2 – Final germination percentage (%) of the experimental tests to study the sexual propagation of the target species

	Treatments								
Species	**Seeds per trial**	**Control**	**Mechanical scarification**	**Cold water immersion**	**Mechanical scarification + water immersion**	**GA_3 treatment**	**Hot water scarification**	**Boiling water scarification**	**Cold Stratification**
Anthyllis lemmaniana	1000*	–	97.8% (December); 39.3% (June)	–	–	–	–	–	–
Armeria maderensis	255 (control) 20-30*	36.9% (December); 41.7% (June)	–	3.6% (10h); 21.1% (12h)	–	–	–	–	98.0%
Cedronella canariensis	50 (*; mechanical scarification) 30 – 500 (*; cold water immersion) 30 (scarification + immersion)	–	57.1%; 46%	5.8% (3h25); 7% (18h); 0% (10h); 100% (102) (12h)	13.3%	–	–	–	3.3%
Genista tenera	450 - 511 10 (*; hot scarification)	24.2%	–	–	–	–	56.2 – 91.6%	3.1%	–
Helichrysum melaleucum	Seeds were not summed	0%	–	–	–	–	–	–	–
Pericallis aurita	1000 (control) 2000*	5.3%	16.8% (September) 29.5% (December)	23.5% (12h)	–	–	–	–	–
Sideritis candicans	40 (*; control) 20 – 30*	72.5% (light); 20% (shade); 36.4-70%; 46.7% (January)	12.5%	25% (10h); 17.2% (24h)	–	25% (T_{amb}); 70% (3°C)	–	–	–
Teline maderensis	20*	–	–	–	40 - 50% (1h30)	–	73.3% (5 min, August); 55 – 85% (5 min, November); 36.4% (10 min)	–	–

If no treatment is mentioned, seed number is applied in all seed treatments. * Indicates trials with 2 to 6 duplicates.

The following are details of seeds pre-treatment:

a. Mechanical scarification – the seeds were rubbed between two sheets of fine–grained sandpaper;
b. Cold-water treatment – the seeds were immersed for different periods, ranging from 30 minutes up to 24 hours, depending on the species;
c. Mechanical scarification plus water treatment – combination of sandpaper scarification, followed by water immersion for 90 min up to 6 h;
d. GA_3 treatment – the seeds were immersed in a 100 ppm solution of GA_3 for 72 h, either at room or cold temperatures (3°C);
e. Scarification with hot water – boiling water was poured for 5 or 10 min on the seeds placed in a glass container;
f. Scarification with boiling water – the seeds were placed in a small strainer and immersed in boiling water (100°C) for 1 min.

An additional treatment was applied to *A. maderensis* and *C. canariensis*, consisting of the seed cold stratification at a temperature between 1 – 6ºC, for 3 months and 1 month respectively, by placing the seeds on a layer of filter paper soaked in distilled water in a sterile Petri dish.

After the treatment, the seeds were sown in germination trays filled with a substrate mixture of soil, peat and perlite (2:1:1), which was used in the majority of the germination trials. For *A. maderensis* and *S. candicans* a different substrate composition was also tested that included the addition of gravel to the substrate (soil, gravel, peat and perlite, with a ratio of 2:2:1:1).

All the seeds were thoroughly cleaned except for *A. maderensis*, whose seeds were tested with and without their papery bracts.

The germination trays were covered with a glass sheet to maintain humidity and were watered every two days.

The seeds were considered germinated with the radicle emergence through the seed coat (TAIZ & ZEIGER, 2010).

Each trial had duration of six months for *A. lemanniana*, *C. canariensis* and *H. melaleucum*, and ten months for *A. maderensis*, *G. tenera*, *P. aurita*, *S. candicans* and *T. maderensis*.

The number of days to germination of 50% of all germinated seeds (T_{50}) was calculated according to the following formula of BACCHETTA *et al*. (2008):

$$T_{50} = [(N/2 – N_1) (T_2 - T_1)] + T_1 / N_2 – N_1$$

where, N is the final number of emergence and N_1 and N_2 the cumulative number of seeds germinated by adjacent counts at times T_1 and T_2 respectively, when $N_1 < N/2 < N_2$. The T_{50} values were not calculated when germination was below 5%.

Vegetative propagation trials

Vegetative propagation of *C. canariensis*, *E. maderensis*, *G. tenera*, *H. melaleucum*, *P. aurita*, *S. candicans* and *T. maderensis*, were carried out between June 2011 and April 2012. *A. lemanniana* and *A. maderensis* were not considered suitable for vegetative propagation due to their characteristics, that involve little or no vegetative spread and their highly herbaceous nature.

Simple cuttings were tested for all of the six species in the vegetative propagation trials. Additional approaches included trench layering for *C. canariensis* and *P. aurita*, and heel cuttings for *T. maderensis*. The number of cuttings *per* test was not standardized due to the scarcity of some species in nature, and therefore, their collection in nature was made considering the number of individuals available in the wild populations in a sustainable approach.

To prepare stem cuttings, a slant angle cut was made just below a node and the leaf area was reduced, leaving only 2 – 3 apical leaves. For cuttings that were taken from the middle portion of a branch, a straight cut was made in the apical portion to reduce water loss. Layering was prepared by wounding the nodes. The cuttings were tested with indole-3-butyric acid (IBA) or potassium salt of indole-3-butyric acid (KIBA) and without the rooting hormones. A powder formulation of IBA with different concentrations of IBA was used according to the type of cutting, namely 0.1% w/w IBA for softwood cuttings (IBA 0.1%), 0.3% w/w IBA for semi–hardwood cuttings (IBA 0.3%), and 0.8% w/w IBA for hardwood cuttings (IBA 0.8%).

Cuttings were established in a substrate mixture of soil, peat and perlite (2:1:1). All cuttings were bed in substrate mixture, either in small plastic bags or in styrofoam boxes covered with a glass sheet in order to maintain humidity until the establishment of rooting. The cuttings were watered every two days.

Cedronella canariensis and *P. aurita* were tested for two methods of vegetative propagation: simple stem cuttings (softwood) with a slant angle, as well as trench layering. For the stem cuttings the difference between the absence of hormones and IBA 0.1% was tested. For the trench layering trial, no hormones were used. For the *C. canariensis* tests, 35 cuttings were used for the IBA 0.1% trials and 421 cuttings for the simple cuttings without the hormones. Forty-three cuttings were tested using the layering method. In *P. aurita*, simple cuttings without hormones were used on 17 cuttings, while IBA 0.1% was applied on 46 cuttings. For the layering method, 10 cuttings were tested for each trial (with and without hormones).

Erica maderensis cuttings (hardwood) were tested either without hormones or with IBA 0.8%. For this species each trial consisted of 20 cuttings.

The heel cutting method was applied to *G. tenera*, both softwood and hardwood cuttings, both without hormones, and with IBA 0.1% and 0.8%, respectively. For this species each trial was performed with 25 to 40 cuttings.

For *H. melaleucum*, 1 cm of the epidermal layer from the lower portion of the semi–hardwood cutting was removed in order to increase rooting success (DRAGOVIC, 2009) and dipped in KIBA (500 ppm) or IBA (1,000 ppm), both for 5 seconds. For this species each trial consisted of 20 to 30 cuttings.

For *S. candicans*, semi–hardwood stem cuttings were tested with a quick–dip in IBA (1000 ppm) for periods of 5, 7 and 10 seconds and KIBA (500 ppm) for 7 seconds. For this species, the trial using IBA was performed with 20 cuttings and those using KIBA consisted of seven to nine cuttings.

Teline maderensis was tested for two approaches of the vegetative propagation: simple stem cuttings with a slant angle as well as the heel cutting. For the semi–hardwood stem cuttings the difference between no hormones and a quick–dip in IBA (1,000 ppm) for 10 seconds was tested. For the heel cuttings, IBA 0.1%, 0.3% and 0.8% were used, respectively for softwood, semi–hardwood and hardwood cuttings. For this species each trial was performed on 20 to 43 cuttings.

Results

Seed propagation

The results of seed propagation trials are summarized in Table 2.

Seeds of *Anthyllis lemanniana* were submitted to only one treatment based on the literature data and therefore the control test was not performed. Mechanical scarification was applied in two distinct seed trials (one in June and one in December). We observed that the chosen propagation method was more effective in December, with a success rate of 97.8% (Table 2).

On the other hand, T_{50} was lower in June (5.65 days) by comparison with December (11 days).

Armeria maderensis seeds were tested using three treatments, namely control, cold-water immersion and cold stratification. We found that the highest success rate was reached in seed trials with cold stratification (98.0%, Table 2). The second highest success rate was achieved without any seed treatment, i.e., control (41.7% in June, and 36.9% in December). This species T_{50} showed a high range, fluctuating between 12,65 (control, December) and 63.08 days (control, June); and cold-water immersion yielded a T_{50} of 71.66 days. Regarding trials with cold stratification, T_{50} values were not calculated since all the seeds germinated at approximately the same time, and therefore the formula was not applicable.

Cedronella canariensis seeds were subjected to five treatments (Table 2). Control tests were not performed based on the seed hardness that would make the seed unable to imbibe water, and therefore, unable to germinate. In these cases, the seed usually requires some other kind of treatment to germinate. The most successful was water immersion for 12 h resulting in 100% germination. Mechanical scarification appeared to be the second best method, yielding 57.1% germination. The remaining treatments resulted in a lower germination success, between 0% and 46.0%.

C. canariensis T_{50} values were high. The mechanical scarification treatment attained 90.34 days, while water immersion T_{50} values ranged between 84.25 days (18h), 89.27 days (3h 25 min) and 102 days (12h). Regarding the treatment that combined mechanical scarification and water immersion, all the seeds germinated at approximately the same time, and therefore the formula was not valid and the T_{50} value was not calculated.

Genista tenera germination was tested under three seed treatments, namely, control, immersion in hot water 5 min, and immersion in boiling water 1 min. The most successful was hot water scarification for 5 min, leading to germination between 56.2% and 91.6% (Table 2). The lowest success rate was achieved with the boiling water scarification for 1 min (3.1%). This species trials showed low T_{50} values, namely 13.66 days for the control treatment, and from 13.53 up to 27.08 days for the hot water scarification treatment.

Helichrysum melaleucum tests were deemed unsuccessful with no germination established.

Pericallis aurita seeds were exposed to three seed treatments (Table 2). The best result was attained with the mechanical scarification with a low success rate of 29.5% in December, whereas in September this value was even lower, reaching 16.8% germination. Water immersion yielded 23.5% (August), and control treatment achieved only 5.3%.

P. aurita T_{50} values were similar amongst treatments, with values between 16,16 (December) and 30.89 days (September) with mechanical scarification, with these values increasing with the decrease of germination success. The water immersion trials showed a T_{50} of 28.5 days.

Sideritis candicans seeds were subjected to four treatments, namely control, mechanical scarification, water immersion, and GA_3 dipping either combined with cold stratification at 3°C or sown at room temperature (Table 2). A test was made to verify the best period of the year for the propagation of this species. The highest success rate was achieved in the control trial in August (72.5%), and the tests performed in early January showed 70% germination. On the other hand, control trials performed in September showed lower germination success, between 38.36 and 40%. A test was performed (August) in order to explore the effect of light without seed treatment. We found that light led to a higher germination (72.5%) than the shade conditions (20.0%, Table 2). Another treatment that showed high germination success was GA_3 dipping combined with cold stratification with a 70.0% germination success.

This species yielded different T_{50} values depending on the treatment applied to the seeds. The lowest T_{50} values were found in the seeds treated with GA_3, namely 11 days at 3°C and 19.5 days at room temperature. In the control trials, the lowest T_{50} were from tests performed in January (15.28 days), whilst trials performed between August and September yielded values between 20 and 76.5 days. Concerning T_{50} values found in the other trials, the mechanical scarification trials were found to have a T_{50} of 43.5 days, whilst water immersion reached 29 days.

Teline maderensis seeds were subjected to two treatments, namely to hot water immersion of different durations, and a combination of warm water immersion and mechanical scarification (Table 2). The test with the best results was immersion in hot water for 5 min, with success rates between 55.0% and 85.0%. On the other hand, hot water immersion for 10 min lowered germination to 36.4%. The combination of warm water immersion and mechanical scarification resulted in 40.0 up to 50.0% germination.

T. maderensis T_{50} lowest values were observed with the 5 min hot water treatment, being the lowermost in August (20 days) followed by November (30.11 days). The 10 min trials yielded a T_{50} value of 38 days, and the combination of warm water immersion and mechanical scarification reached 31.67 days.

Regarding the statistical tests, the results demonstrated that there was no statistical difference between treatments, except for *G. tenera*, with a p-value of 0.025 in the one-way ANOVA test.

Vegetative propagation

The results of plant vegetative propagation are summarized in Table 3.

Cedronella canariensis vegetative propagation was performed between May and November using two methods, the simple stem cuttings and the trench layering (Table 3). IBA 0.1% was applied only in May, since the cuttings using this hormone showed a low success rate (3.0%). Regarding cuttings without hormones, the highest success rate was reached in November (48.2%), followed by August and July, both with 41.0% success. The lowest success rate was achieved in May (33.0%). We found that in most cases the rooting occurred within a month from the commencement of the treatments. The trench layering method had the highest success rate in July (30.8%) followed by June (20%).

Propagation success of *Helichrysum melaleucum* greatly depended on the time of experiment (Table 3). Cuttings made in May had a success rate of only 4.0%. On the other hand, cuttings prepared in August showed a 60.0% success rate. These results were achieved only with a 5 second quick–dip in KIBA (500 ppm) since the cuttings tested with IBA (1000 ppm) did not root at all.

In *Pericallis aurita*, the most successful treatment was trench layering with and without hormones (60% and 80%, respectively) (Table 3). On the other hand, simple cuttings proved to be a less effective method, not reaching, overall, higher than 36.9%.

Sideritis candicans cuttings attained a general yield of 47.8% (Table 3). The highest success rate was achieved in May, with a 5 second quick–dip in 1000 ppm IBA (75.0%), followed by trials made in June (70.0%). Cuttings made in August showed a lower success rate, between 10.0% (10 sec quick–dip in 1000 ppm IBA) and 50.0% (5 sec. quick–dip in 1000 ppm IBA), where only rooting nodules where observed. However, due to this species scarcity in nature, few cuttings were tested.

The lowest success of vegetative propagation was recorded for *G. tenera*, *T. maderensis* and *E. maderensis* (all 0%), with the cuttings dying within a month.

In the statistical tests performed for vegetative propagation, the results demonstrated that there was no statistical difference between treatments.

Table 3 – Rooting percentage (%) of the experimental studies of the vegetative propagation treatments applied to each species

Species	Treatments							
	Stem cuttings –No treatment	Stem cuttings – IBA 1000 ppm	Stem cuttings – KIBA 500 ppm	Softwood stem cuttings – 0.1% p/p IBA	Semi-hardwood stem cuttings - 0.3% p/p IBA	Hardwood stem cuttings – 0.8% p/p IBA	Trench layering	Heel Cutting
Cedronella canariensis	33.0 – 48.2%	–	–	3.0%	–	–	20.0 – 30.8%	–
Erica maderensis	0%	–	–	–	–	0%	–	–
Genista tenera	0%	–	–	0%	–	0%	–	–
Helichrysum melaleucum	–	0%	7.6% (May); 72% (August)	–	–	–	–	–
Pericallis aurita	29.4%	–	–	36.9%	–	–	60.0% (with hormones); 80.0% (without hormones)	–
Sideritis candicans	–	70.0–75.0% (5 sec dip); 22.2% (7 sec dip); 25.0% (10 sec dip)	42.9% (7 sec dip)	–	–	–	–	–
Teline maderensis	0%	0%	–	0%	0%	0%	–	0%

Discussion

There is very little previously published information regarding propagation features of the studied Madeiran species. These species employed several germination strategies, and in the majority of cases, germinated under a variety of settings achieving the highest success under specific conditions. This is consistent with prior findings reporting relationships between the seed traits, dormancy and habitat among species of close genera (MAYA *et al.*, 1988; DOUSSI & THANOS, 1993, 1994; PRESS & SHORT, 1994; THANOS & DOUSSI, 1995; IBAÑEZ & PASSERA, 1997; HANLEY & FENNER, 1998; HEIMBINDER, 2001; AYANOĞLU *et al.*, 2002; ESTRELLES *et al.*, 2004, 2010; PRIETO *et al.*, 2004; GARCÍA *et al.*, 2005; LOPES *et al.*, 2005; SERRANO-BERNARDO *et al.*, 2007; BONNER *et al.*, 2008; MORBIDONI *et al.*, 2008; CERVELLI, 2009; PAPAFOTIOU & KALANTZIS, 2009; KADIS *et al.*, 2010; UÇAR & TURGUT, 2011), as well as habitat of origin (PRESS & SHORT, 1994; JARDIM *et al.*, 2007).

The germination success ranged from 70.0% (*A. lemmaniana*, *A. maderensis*, *C. canariensis*, *G. tenera*, *S. candicans* and *T. maderensis*) to 0% (*H. melaleucum*), while *P. aurita* showed an intermediate germination success (29.5%).

The vegetative propagation does not appear to be an ultimate reproductive strategy within three species that showed no rooting success, and only four species reaching a rooting success higher than 60%.

Anthyllis lemanniana commenced germinating only after a certain period of time after mechanical scarification. These observations point to the assumption that mechanical scarification mimics this species habitat (rocky cliffs in the highest altitudes of the island) and the need for cold temperatures to trigger germination. Therefore, it is safe to assume that the main factors affecting this species germination are the temperature and breaking seed coat dormancy. This is also supported by previous reports documenting that a major characteristic of the *Anthyllis* genus is seedcoat hardness, hence primary dormancy could be broken by the mechanical scarification (DOUSSI & THANOS, 1993, 1994; IBAÑEZ & PASSERA, 1997; HANLEY & FENNER, 1998; PRIETO *et al.*, 2004; MORBIDONI *et al.*, 2008).

In *Armeria maderensis* dormancy breaking treatments were needed to achieve germination success. Plant seeds exhibited a higher germination rates after cold stratification (98.0% germination success), leading to the break of seeds thermodormancy (secondary dormancy). This fact can be correlated with this species habitat in the highest peaks of the island, up to 1,860 m a.s.l. (PRESS & SHORT, 1994; JARDIM & FRANCISCO, 2000).

Cedronella canariensis seeds showed the highest success rates after water immersion (12h, 100%) and mechanical scarification (57.1%). These results point to the water availability and uptake as key requirements for seeds germination, which is consistent with species habitat, where water is typically available in abundance. Therefore, it can be assumed that this species displays physical dormancy (primary dormancy). In fact, germination tests performed by ENSCOBASE (2011) showed that scarification of the seeds (chipped with scalpel) lead to germination between 46 and 100%, whilst the use of sole GA_3 lead to germination success of only 5 to 26%, proving the need for scarification. On the other hand, *C. canariensis* seems to be easily propagated by simple softwood (herbaceous) stem cuttings without rooting hormones requirement, which can be used as an alternative strategy of plant reproduction.

Erica maderensis vegetative propagation trials were unsuccessful. This could point to an existence of a persistent seed bank sufficient to assure survival of the species, and therefore, the plant did not develop robust vegetative reproduction strategies. Additional experiments involving the treatment with heat or smoke could shed some more light on the details of reproduction tactics of *E. maderensis*, since it has been observed that *Ericaceae* species are more prone to reproduce vegetatively after disturbances, such as fires (VALBUENA & VERA, 2002; PAULA & OJEDA, 2006, 2009). A research conducted by PAULA & OJEDA (2009), who studied the aboveground and belowground response of three species of *Erica*, *E. australis* L., *E. scoparia* L., and *E. arborea* L., and their capacity to resprout after disturbances revealed that the belowground (root) starch reserves are more crucial for resprouting when compared to the aboveground biomass.

Genista tenera propagation tests showed that this species seeds requires hot water scarification (5 min) treatment to break physical dormancy imposed by a hard seedcoat. Such treatment resulted in effective germination (between 66.7 and 91.6 %) since the heat was used to soften the seedcoat. These conditions mimicked high temperatures experienced by the plant during the summer reproductive period. Similar results have been obtained with *Genista* species, namely *Genista monspessulana* (L.) L. Johnson, where heat-treated seeds with boiling water germinated rapidly with over 50% of germination (ZOUHAR, 2005). A study performed on several species of the *Genistae* tribe showed that in general, the germination success was improved for nearly all of the *taxa* when scarifying agents (such as sulphuric acid) were applied (LOPEZ *et al*., 1999), substantiating the need for scarifying in order to break dormancy of these species. On the other hand, vegetative propagation proved to be an ineffective reproductive strategy for *G. tenera*.

Teline maderensis seed propagation tests showed a great similarity with the results obtained for *G. tenera*, with the seeds requiring hot water scarification (5 min) to remove physical dormancy. As with *G. tenera*, vegetative propagation of *T. maderensis* species was also unsuccessful, perhaps due to these species vegetative regeneration strategy. Species of the Fabaceae usually reproduce by vegetative means sporadically, after being subjected to a disturbance such as a fire, when typically the upper part of the plant is destroyed, and thus allowing for the vegetative reproduction to be initiated from the neck or base of the root system (SAHA & HOWE, 2003; ZOUHAR, 2005; REYES *et al*., 2009). This has been observed in other species of the *Genistae* tribe such as *Genista triacanthos* Brot., *Ulex minor* Roth and *Ulex europaeus* (L.) (REYES *et al*., 2009). Therefore, cuttings from their branches would hardly lead to a rooted cutting. This is in agreement with the observation that *G. tenera* and *T. maderensis* seeds germinated better under high temperature conditions.

Helichrysum melaleucum shows to have low seed productivity, and few viable seeds were found in nature. We observed that seeds of this species were heavily affected by pest feeding on the inflorescence and seeds, making seed availability scarce. The 0% germination obtained in seed trials without treatments can be explained by the seeds non–viability, or the need to combine factors or treatments to break their dormancy. Thus far, there has not been any attempt to propagate this species.

Studies conducted with species belonging to the same genus, *Helichrysum gossypinum* Webb., a Canary Island endemic, have shown that germination of this species could be mainly influenced by temperature (MAYA & PONCE, 1989). Another study with *H. gossypinum* and *Helichrysum monogynum* Burtt & Sunding, another endemic species of the Canary Islands, showed that without any seed treatment, only the latter species showed 20.0% germination (MAYA *et al*., 1988). In the same study, the use of GA_3 leads to germination of 27.5% of *H. gossypinum* and 12.5% of *H. monogynum* seeds (MAYA *et al*., 1988). However, it has been observed in nature and the gardens that seeds of this species sprout near the mother plant. We hypothesize that the mother plant could establish some interactions with soil rhizosphere, thus increasing the seed germination success. At the same time, vegetative propagation was mediocre, with 60% rooting success in the presence of KIBA (500 ppm). Vegetative propagation of *H. melaleucum* appears to be dependent on the time of year, as it has been already shown by DRAGOVIC (2005a; 2005b; 2009) in other *Helichrysum* species of Madeira. Therefore, it appears that the best propagation method of this species would be vegetative propagation due to its low seed germination.

Pericallis aurita seeds required mechanical scarification treatment to break seed dormancy in order to reach of 29.5% germination success, thus displaying physical dormancy, probably due to a hard seedcoat. Interestingly, a study performed by BAÑARES *et al*. (2003) with the germination of *Pericallis hansenii* (Kunkel) Sunding, a Canary endemic closely related to *P. aurita*, showed very different results. In these trials, the control tests resulted in 59.5% germination, whilst germination augmented with the hormone treatment (GA_3) reached 84%. However, since the germination success of *P. aurita* is fairly low, the plant could rely on vegetative propagation as a reproductive strategy. Simple stem cuttings and trench layering, regardless of the use of hormones can reach 90.0% of rooting success. Rooting success seems to have a physiological basis and is season dependent (time of year conditioned). Similarly, the study performed by BAÑARES *et al*. (2003) showed good vegetative propagation results with simple cuttings with the use of IBA 0.10% (80.0% rooting success).

Sideritis candicans does not require any sort of seed treatment to achieve high germination success, regardless of time of year, light conditions and cold stratification. On the other hand, a study performed with two Iberian *Sideritis* species, *Sideritis pungens* Benth. and *Sideritis chamaedryfolia* Cav. showed that germination of these species is affected by temperature, pre-treatment used, and especially light conditions (ESTRELLES *et al*., 2010). The different needs of *S. candicans* could be due to the diverse environments of the species, since *S. pungens* grows in sub–humid high mountains (1,000 – 2,000 m a.s.l.) and *S. chamaedryfolia* is found in dry, thermo–mesomediterranean habitats (500 – 850 m a.s.l.) (ESTRELLES *et al*., 2010). Likewise, when KADIS *et al*. (2010) studied the germination requirements of *Sideritis cypria* Post, it was shown that temperature was the main factor impacting this species germination, but no additional pre–treatments were required, as in *S. candicans*. In contrast, a study conducted in Bulgaria showed that a species of *Sideritis*, *Sideritis scardica* Griseb., required GA_3 to germinate (80.9%), whilst seeds with no treatment did not germinate at all (KOZUHAROVA, 2009). This plant also shows an effective vegetative propagation, most efficient, when simple cuttings are combined with a 5 second quick-dip in 1000 ppm of IBA (70 – 75%), preferably in late spring – early summer.

The statistical tests generated results that are in contrast with the field observations, showing that there was no statistical difference between treatments, both in seed propagation and vegetative propagation. These divergences between field results and statistical results could be due to the use of samples to small or insufficient to detect any effect in statistical tests, i.e., the trials and their effects were with an inadequate sample size, thus providing a false negative (KANYONGO *et al*., 2007; RITCHIE *et al*., 2011; REINHART, 2012; COLQUHOUN, 2014).

Overall, physical dormancy appears to be the most common type of dormancy displayed by the nine native Madeiran species studied in the present work. At the same time, the major ecological constraints to seed germination are represented by temperature and water availability. Physical dormancy of hard seedcoat species (*A. lemanniana, C. canariensis, G. tenera* and *T. maderensis*) appears to be mainly due to inability of the seeds to imbibe water.

We were able to verify that the mechanical scarification is a suitable method for *A. lemmaniana* and *P. aurita,* while *G. tenera* and *T. maderensis* require hot water scarification for 5 min. On the other hand, *A. maderensis* requires cold stratification and *C. canariensis* could be propagated either by the mechanical scarification or cold water immersion. Interestingly *S. candicans* does not require any seed treatment to germinate, even though the application of GA_3 also gave positive results. The only species that did not show any germination was *H. melaleucum*, in which the lack of viable seeds led to insufficient germination trials. Therefore, sexual propagation of this species requires further studies.

Vegetative propagation appears to be a method applicable to only a few species with rooting success higher than 50% in only three species, namely *H. melaleucum, P. aurita* and *S. candicans*, followed by *C. canariensis*, reaching near 50 % success. All tested species adopted different vegetative regeneration strategies – *C. canariensis* does not require rooting agents and is propagated by simple stem cuttings, *H. melaleucum* requires KIBA (500 ppm) and propagates better in the summer, *P. aurita* is best propagated by the trench layering, and *S. candicans* with a 5 sec. dip in IBA 1,000 ppm.

Acknowledgments

José Manuel Rodrigues and other staff from the Ecological Park of Funchal, Sónia Ferraz, Marta Moreira and Filipe Ganança from the ISOPlexis Genebank, and the staff of the Floriculture Centre. We thank Jan J. Slaski of the ISOPlexis Genebank and the Alberta Innovates Technology Futures for reviewing the manuscript.

Abbreviations used: m - meters; a.s.l. - above sea level; GA_3 - gibberellic acid; IBA - indole-3-butyric acid; KIBA - potassium salt of indole-3-butyric acid; IBA 0.1% - powder formulation of 0.1% w/w IBA; IBA 0.3% - powder formulation of 0.3% p/p IBA; IBA 0.8% - powder formulation of 0.8% w/w IBA; ppm - parts-per-million (10^{-6}), h – hour(s); min - minute(s); sec - second(s); T_{50} - number of days to germination of 50% of all germinated seeds; N - final number of emergence; N_1 - seeds germinated when $N_1 < N/2$; N_2 - seeds germinated when $N/2 < N_2$; T_1 time $N_1 < N/2$; T_2 – time $N/2 < N_2$.

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Entregue para publicação em setembro de 2015
Aceite para publicação em maio de 2017

Silva Lusitana, **25**(*1*): *79 - 105, 2017*

An Ecological Approach to the Management of Mixed Uneven-Aged Forests

Luís Soares Barreto

Abstract. The author sustains the following statement: it is presumable that the dynamics of mixed uneven-aged natural stands, this is, with species that had coevolved, is very predictable, evince small sensitivity to the proportions of the species, and have behaviour close to a pure stand. He analyses the close competitiveness of species in natural mixed stands, and shows that its main consequence is adaptability. He proposes procedures to model mixed uneven-aged stands, with or without explicit size structures of the age classes.
Key words: adaptability, coevolution; modelling, mixed uneven-aged forests

Uma Abordagem Ecológica do Ordenamento das Florestas Mistas Irregulares

Sumário. O autor demonstra a seguinte asserção: é presumível que a dinâmica dos povoamentos naturais mistos irregulares, isto é, aqueles em que as suas espécies tenham passado por um processo de coevolução, seja predizível, tenha pouca sensibilidade ás proporções das espécies, e tenha um comportamento muito semelhante à dos povoamentos puros. Analisa a competitividade muito próxima das espécies, nestas florestas, e mostra que a principal consequência é a adaptabilidade. Propõe procedimentos para modelar os mesmos povoamentos sem ou com estruturas dimensionais das classes de idade.
Palavras-chave: adaptabilidade, co-evolução, florestas mistas irregulares, modelação

Un Abordage Ecologique de l'Aménagement des Forêts Mixes Irrégulières

Résumé. L'auteur soutien que les forêts mixes irrégulières naturelles ont une dynamique prévisible, et peu sensible à les proportions des espèces. Aussi, ces forêts ont un comportement identique à des forêts pures causé pour la proche compétitivité de ses

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espèces. Cette similitude compétitive est la source de son adaptabilité. L'auteur propose des méthodes pour la modélisation des peuplements mixes irrégulières, avec ou sans structures dimensionnelles des classes d'age.
Mots-clés: Adaptabilité, co-évolution, forêts mixes irrégulières, modélisation

Introduction

Echoing other researchers, in their recent and interesting book, PUETTMANN, COATES, and MESSIER (2009) state that the transposition of ecological knowledge into managerial practice, in the area of natural resources, had not been as successfully as desired. The scope of this paper is to present a tentative contribution to attenuate this situation, in the area of forest management.

My focus is in the sub community of trees. Independently of the indisputable importance of the all community, there is no any embracing nomomlogical construct to approach it. Several characteristics of ecology contribute to its meagre nomological structure, commented, for instance, in the entry "ecology", in the Stanford Encyclopedia of Philosophy, accessible in the Internet (SARKAR, 2009).

The aim of the present text is also in consonance with the actual paradigm of forestry, oriented for the multifunctional management of mixed uneven-aged natural forests (MUNF), where selective cuts of few trees are executed.

Underpinned by available ecological knowledge, and my unified theory for forest stands, both pure, and mixed, even-aged, and uneven-aged (BARRETO, 1997, 2003a, b, c, 2004a, b), I will attempt to sustain the following basic contention: *Considering deterministic archetypes of mixed uneven-aged* ***natural*** *stands, this is, with species that had* ***coevolved,*** *it is presumable that their dynamics are very predictable, evince small sensitivity to the proportions of the species, and have behaviour close to a pure stand.*

I admit that MUNF are complex systems, but do not possess complicatedness. Thus, they evince emergent simplicity.

I will take advantage of my contention, to propose ecologically sustained guidelines to the management of MUNF.

This article is a follow up of Barreto (Forthcoming).

For the elaboration of this paper, I used Scilab 5.1 (COSORTIUM SCILAB, 2009) as a simulation platform (BARRETO, 2008b; CAMPBELL, CHACELIER, NIKOUKHAH, 2006).

The close competitiveness of species in MUNF

My analyses of natural mixed stands show that their species have very close competitive ability. This does not surprise, and agrees with the doctrine presented in textbooks of ecology. For instance, in ODUM, and BARRETT (2005) is stated that evolution of communities tend to minimize negative interactions among the populations in coexistence. I other words, coevolution promotes fitness, as very often repeated in ecological texts, and papers.

Let me emphasize the ecological and systemic consequences of the mitigation of the competitive situation.

1. The trees of a given species, in mixed stands, experience an interspecific competitive situation very close to intraspecific competition. See figure 1, below.
2. Thus, its dynamics in mixed even-aged stands can me modelled with the Gompertz equation with negligible discrepancies. Given the time-space symmetry, their populations in MUNF abide also the Gompertz equation in space, when the stable age structure is attained.
3. From 1., in a MUNF, the sensitivity of the parameters of a given population (age class mortality, transition to the next class, and permanence in the class, for a given period of time) to the proportions of the species, is very low, as I will illustrate ahead.
4. Consequently, when the number of trees of a given species, due to any cause, is drastically reduced, the chances of being eliminated by interspecific competition are extremely reduced, and the biodiversity is preserved.

Thus, the result of the attenuation of the competitive struggle in natural mixed stands is the reinforcement of the homeostasis, and resilience of the system, and by consequence the adaptability of the complex system is enhanced. Adaptability is supervening to the close competitiveness of the species that had coevolved. It may be seen as a paradox that the community of the trees, to guarantee its unchanged persistence, must behave close to a pure stand.

As many time emphasized, evolution and ecology are intimately tied. The primal engine of the stable specie richness of communities is a plethora of both resources and time. Time promotes the accommodation of the growth rates, the emergence of local ecological isolation mechanisms (e.g., COLLIER, COX, JOHNSON and MILLER, 1973), and mutualism. Thus, it is my understanding that the coevolution factor, and its implications, can not be ignored when analysing the properties of communities, such as stability and persistence. The history of the connectivity is also relevant.

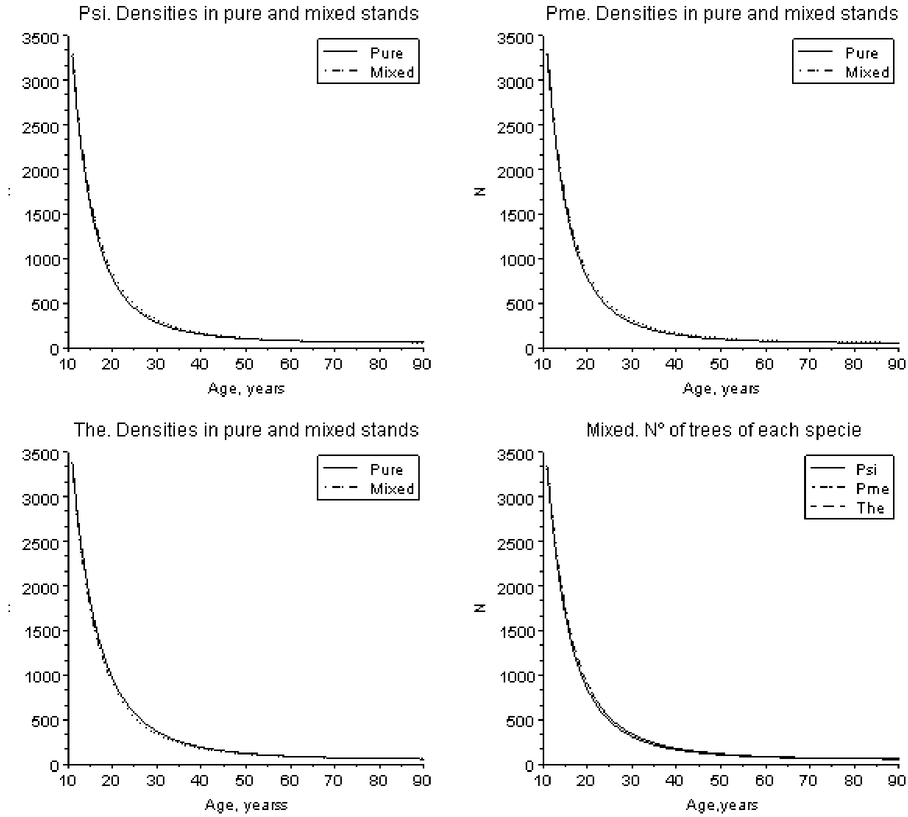

Figure 1 - Simulation of a North-American natural mixed even-aged forest with *Picea stchensis* (Psi), *Pseudotsuga menziesii* (Pme), and *Tsuga heteropylla* (The). At age 10, each population has 4000 trees. Model BACO2 was used. For comparison, I simulated also a pure similar stand of each species. Numbers of trees at age 90, respectively pure and mixed as Psi: 60, 59; Pme: 54, 58; The: 60, 61

A Model for Tree Competition

Although my theory for pure and mixed stands is described elsewhere (e.g., BARRETO, 2003a, 2004a, b), I present a brief description of my model for tree competition, for the sake of completeness and clarity.

First let me introduce the notation for the forest variables in pure and mixed stands. The variables in pure and mixed stands are, respectively, mentioned by y_{ijt}, and y_{sijt}, where i is the power of the linear dimension associated to the variable; j is the identifier of the variable; t is age, as usual; s, in mixed stands, refers to a given species. In table 1, I describe the variables.

Table 1 - The description of the variables of trees, and a population of trees

A. Tree variables							
i=1		i=2		i=2.6666		i=3	
j	Variable name	j	Variable name	j	Variable name	j	Variable name
1	Dbh	1	Leaf biomass	1	Total tree biomass	1	Stem volume
2	Height	2	Biomass of live branches			2	Biomass of the stem wood
2d	Dominant height	3	Biomass of dead branches			3	Biomass of the stem bark
		4	Total crown biomass			4	Total stem biomass
		5	Leaf area			5	Total root biomass
		6	Basal area				
		7	Area occupied by a tree				
B. Population variables							
i=-2		i=0		i=0.6666		i=1	
j	Variable name	j	Variable name	j	Variable name	j	Variable name
1	Trees/hectare	1	Leaf biomass/ ha	1	Total tree biomass /ha	3	Stem volume /ha
		2	Biomass of live branches/ha			4	Biomass of the stem wood /ha
		3	Biomass of dead branches/ha			5	Biomass of the stem bark/ha
		4	Total crown biomass/ha			6	Total stem biomass /ha
		5	Leaf area/ha			7	Total root biomass /ha
		6	Basal area/ha			8	Tree spacing

In pure stands and mixed stands, tree variables abide the Gompertz equation (GPZ), that can be written as:

$$y_{ijt} = y_{ijf} R_i^{\exp(-c(t-t_0))} \quad (1)$$

where y_{ijf} is the final or asymptotic value of y_{ij}. $R_i = y_{ij0}/y_{ijf}$. y_{ij0} is the value of the variable at age t_0, when the competition among trees is dominant, and the variables start their its Gompertzian trajectories. c and R_i are real positive numbers, characteristic of each species. Population variables follow the GPZ only in pure stands, and are very close to this pattern of growth if the stand species had experienced a process of coevolution. Implicit to this statement is the following one: tree competition directly affects the population variables, namely tree mortality, but the tree variables are affected indirectly through the impact of the species upon the site quality related to the target species. This is reflected, *ab initio*, on the regeneration and recruitment of the species, and on the size of the individuals.

It is verified

$$R_a=R_b^{a/b} \tag{2}$$

This equation is responsible for the internal coherence and harmony of the growth of the forest, and its trees. For instance, it guarantees that the space and resources released by self-thinning are fully utilized, without waste.

Given eq. (1), the relative variation rate of variables with power of the linear dimension i is defined as:

$$RVR_i = \frac{dy_{ij}}{y_{ij}dt} = -c\ln(R_i)e^{-c(t-t_0)} \tag{3}$$

$$RVR_a=(a/b)RVR_b \tag{4}$$

Given eq. (4), species that have close relative mortality rates also possess close growth rates.

Under the perspective of the competitive pressure the trees of species i are suffering, the total density of the stand for this species is measured as:

$${}^{m}y_{i-21t} = y_{i-21t} + \sum_{j=1}^{n} \frac{rmr_{jt}}{rmr_{it}} y_{j-21t} \quad j\neq i \tag{5}$$

where $rmr_{it}(=-c_i \ln(R_{i-2}) \exp(-c_i(t-t_0)))$ is the relative (or per capita) rate of mortality of species i, at age t, in a pure stand. The per capita rate of mortality of specie i in a mixed stand, with n species, is defined as:

$${}^{m}rmr_{it} = rmr_{it}(1+\sum_{j=1}^{n} \frac{y_{j-21t}}{YT_t}\ln(\frac{rmr_{jt}}{rmr_{it}})) \quad j\neq i \tag{6}$$

where

$$YT_t = \sum_{i=1}^{n} y_{i-21t} \tag{7}$$

I can write my model BACO2 for tree competition as:

$$\frac{dy_{i-21t}}{dt} = y_{i-21t}\,{}^{m}rmr_{it} \tag{8}$$

Eq. (8) is underpinned by the following conceptual model for tree competition: in a mixed stand, the competitive ability of a species is determined by its growth rate (Grime's hypothesis) and its proportion in the stand. Thus, as R_{-2} decreases from K-strategists to r-strategists, the former species have higher competitive ability than the later. The dominant species transfers a fraction of its inherent mortality to the dominated species ($^{m}rmr<rmr$), which see its mortality accrued ($^{m}rmr>rmr$).

In BARRETO (2003b) I introduced other models for tree competition.

From eq. (5), I propose the Wilson-Barreto stand density index for specie i in a mixed stand, with square spacing, as:

$$F_{WBit} = \frac{\sqrt{Area}}{y_{i12dt}\sqrt{^{m}y_{i-21t}}} \qquad (9)$$

To obtain the value of F_{WB} for triangular spacing multiply the value for square spacing by 1.240806.

The thinning intensity of specie i, where y_{i-21tT} trees are eliminated, for any specie j is measures as:

$$ti_j = \frac{y_{i-21tT}\,rmr_{it}}{^{m}y_{j-21t}\,rmr_{jt}} \qquad (10)$$

I successfully applied model BACO2 to the classical experiments of Gause, with species of *Paramecium* (BARRETO, 2005).

To extend the concepts of equivalent density, equivalent thinning intensity, and the Wilson-Barreto stand density index to mixed uneven-aged forests, considers the trees of each age class of each species as virtual specie.

My theory depicts also the butterfly effect in self-thinned even-aged mixed stands, as illustrated in figure 2, for the standing volume of a forest with *Picea sitchensis* (Psi), and *Pseudotsuga menziesii* (Pme). The initial values of the standing volumes for Psi are 100, 150,...600 m^3, and for Pme are 1200-standing volume of Psi. The trajectories of the standing volumes are clearly divergent. I also exhibit the current annual increments of the two species. The trajectories are reversed. First the current annual increment grows, attains a maximum, and after converges to zero. The simulations ran from age 10 to 510 years.

To complement this section see BARRETO (2003c, 2007).

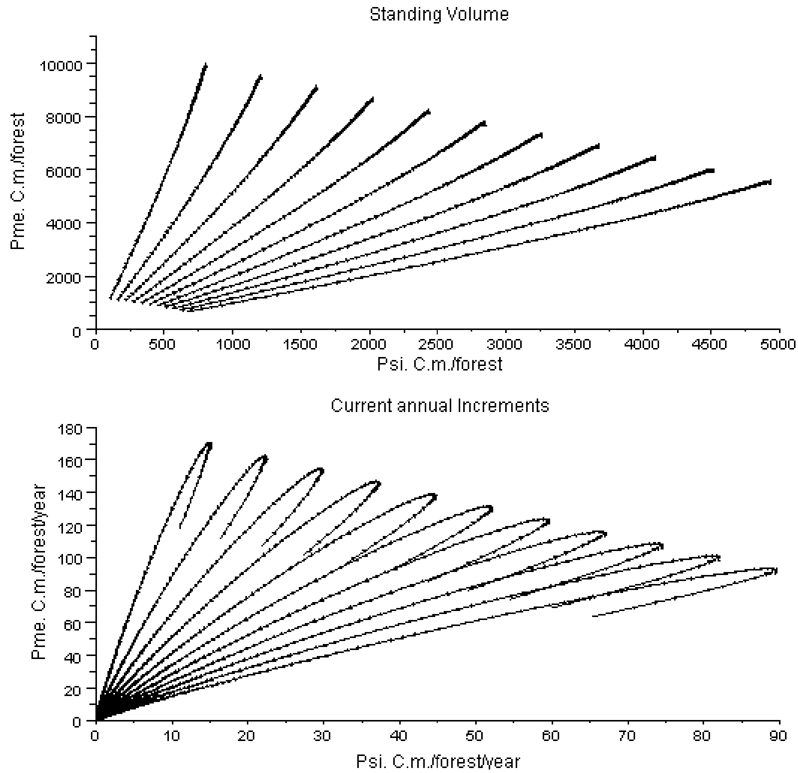

Figure 2 - The butterfly effect illustrated with a forest of *Picea sitchensis* (Psi), and *Pseudotsuga menziesii* (Pme)

Characterizing the Species in Three Mixed Uneven-Aged Forests

To illustrate my contention, I start by considering two MUNF, which exist in nature. One is the European forest with *Quercus robur* (Qro) and *Fraxinus excelsior* (Fex), the other is the North-American forest with *Picea sitchensis* (Psi), *Pseudotsuga menziesii* (Pme) and *Tsuga heterophylla* (The).

In table 2, I exhibit the characteristic parameters of the species, their life-history strategies (BARRETO, 2008a) and their growth, regeneration and survival indices (BARRETO, 2009a). As I will use ahead *Betula pendula* (Bpe), and *Pinus pinaster* (Ppi), I include the characterization of these species in the table 2.

Table 2 - Characterization of the species here considered. LHS=life-history strategy; GI= growth index; RI=regeneration index; SI=survival index; L=longevity, years; NCH=number of competitive hierarchies during the life of the even-aged mixture

Forest	Species	c	R_2	LHS	GI	RI	SI	L	NCH
1	Fex	0.038	87.770	r↔K	6.995	0.001218	0.998782	300	2
	Qro	0.041	125.963	K-2	16.279	0.000259	0.999741	500	
2	Psi	0.048	72.308	K-1	10.210	0.000829	0.999171	750	4
	Pme	0.046	82.196	K-1	10.205	0.000886	0.999114	700	
	The	0.039	81.016	K-1	9.139	0.000895	0.999105	500	
3	Bpe	0.035	20.048	r-3	1.049	0.076772	0.923998	120	1
	Ppi	0.05	6.018	r-3	0.743	0.137657	0.862343	100	

In Figure 3, I show the relative mortality rates of the first, and second sets of species. In each one the values are very close (comparable competitiveness), and are negligible after the age of 100 years. The older trees occupy space but have virtually no competitive impact.

In the MUNF Qro+Fex, the oak is the dominant specie till age 61 years, after the competitive hierarchy is reversed.

In the North-American forest, the shifts of the competitive hierarchy are less simple. For age<14 years: Psi>Pme>The; 14<age<32: Pme>Psi>The; 32<age<34: Pme>The>Psi; age>34: The>Pme>Psi. These shifts of dominance are harmonized with the shade tolerance of the species (BARRETO, 1997).

In the third forest it is always verified Bpe>Ppi.

A Strategy for Analysis

I used my theory to delineate the strategy applied to the solution of my problem, as described by the flowchart inserted in figure 4.

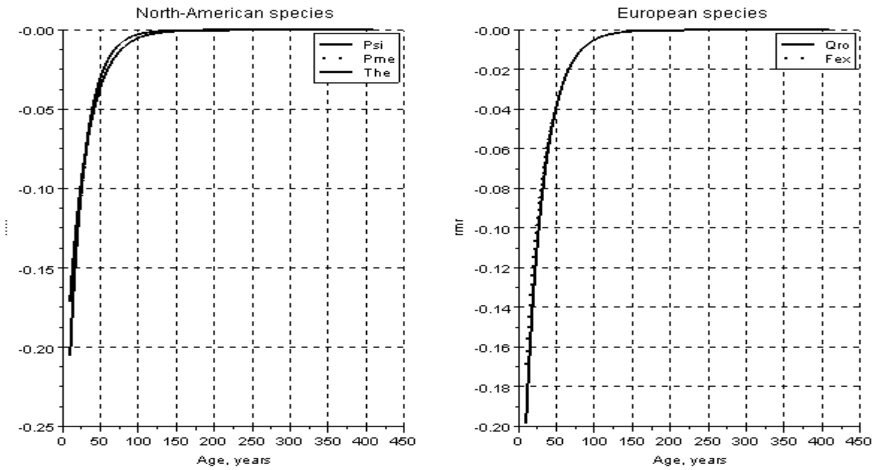

Figure 3 - Relative mortality rates (rmr) of the species of the two first sets

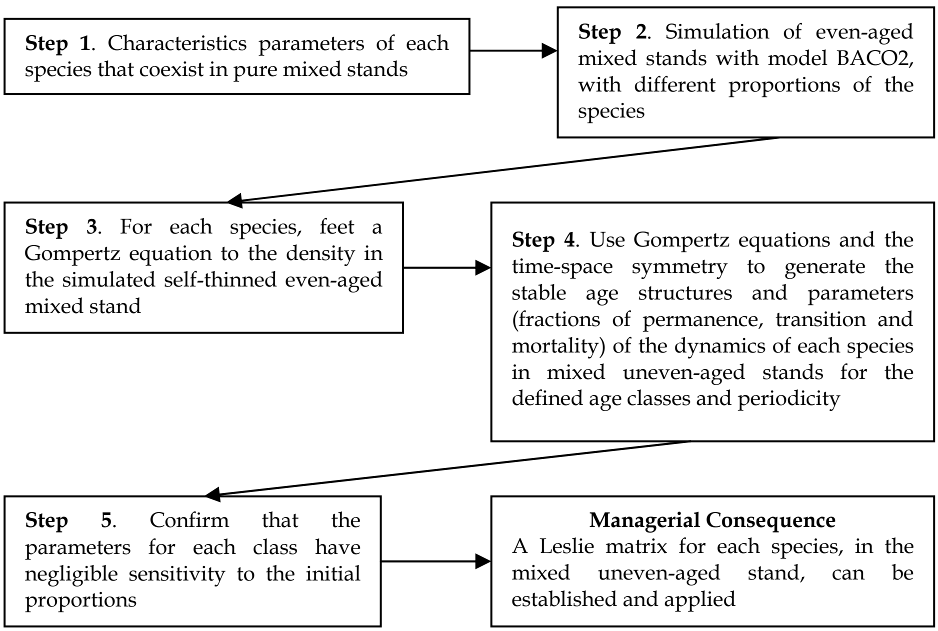

Figure 4 - The schematic description of the procedure applied to satisfy the purpose of the inquiry

The European MUNF

In this section I approach Forest 1, described in table 2.

In BARRETO (2003c), I already presented the parameters of the dynamics of stands with Qro, and Fex, that I will use here. I consider the six following age classes: 10-29; 30-49; 50-69;… 110-129. The MUNF are symmetric of three even-aged mixed stands that, at age 10, have a fraction of trees of the oak equal to 0.2, 0.5, 0.8, and a total density of 10000 trees per are unit. The stands are described in table 3.

From here on, for a period of five years, I will use the following symbology for the trees in a given age class of an uneven-aged stand: M=fraction of trees that die (mortality); T= fraction of trees that move to the next class; P= fraction of trees that remain in the class.

Table 3 - The structure and dynamic parameters of three MUNF of Qro and Fex. Reproduced from BARRETO (2003c)

Class	Trees/ha	Mean dbh	M	T	P
0.2					
Qro					
I	116	10.18	0.604862	0.062986	0.332152
II	17	30.72	0.280137	0.140635	0.579228
III	7	48.14	0.129743	0.194190	0.676067
IV	5	58.21	0.060090	0.223050	0.716860
V	4	63.18	0.027830	0.237284	0.734885
VI	4	65.48	0.012889	0.244061	0.743050
Fex					
I	463	15.64	0.607763	0.062510	0.329726
II	66	34.92	0.280930	0.140401	0.578669
III	28	49.29	0.129856	0.194157	0.675987
IV	19	57.50	0.060024	0.223085	0.716891
V	16	61.71	0.027745	0.237326	0.734990
VI	15	63.76	0.012825	0.244092	0.743083
0.5					
Qro					
I	280	10.06	0.629887	0.058994	0.311119
II	37	30.68	0.286180	0.138900	0.574920
III	16	48.14	0.130021	0.194196	0.675783
IV	11	58.21	0.059073	0.223553	0.717373
V	9	63.18	0.026839	0.237761	0.735400
VI	8	65.48	0.012194	0.244393	0.743413

Table 3 – Continuation

Class	Trees/ha	Mean dbh	M	T	P
Fex					
I	279	15.53	0.629989	0.058978	0.311033
II	37	34.89	0.286203	0.138894	0.574903
III	16	49.29	0.130022	0.194196	0.675782
IV	11	57.50	0.059069	0.223555	0.717376
V	9	61.71	0.026835	0.237763	0.735402
VI	8	63.76	0.012191	0.244395	0.743414
0.8					
Qro					
I	432	9.94	0.654962	0.055202	0.289836
II	53	30.64	0.292088	0.137220	0.570691
III	22	48.14	0.130260	0.194213	0.675526
IV	15	58.21	0.058091	0.224037	0.717871
V	13	63.18	0.025906	0.238208	0.735886
VI	12	65.48	0.011553	0.244699	0.743748
Fex					
I	108	15.42	0.652257	0.055603	0.292140
II	13	34.86	0.291371	0.137428	0.571200
III	6	49.29	0.130159	0.194243	0.675598
IV	4	57.51	0.058144	0.224009	0.717847
V	3	61.71	0.025973	0.238176	0.735851
VI	3	63.76	0.011603	0.244675	0.743722

To verify my basic statement, for each species, I divided the parameters of the classes of the first and third stand by the homologous values of the stand symmetric of the balanced density. The ratios are exhibited in table, 4 and 5.

For the sake of completeness, in table 6, I exhibit the "ratio 0.8/0.2".

Table 4 - The ratios described in the text for Qro

0.2/0.5			0.8/0.5		
M	T	P	M	T	P
0.9602707	1.0676679	1.0676044	1.0398087	0.9357223	0.9315921
0.9788839	1.012491	1.0074932	1.0206443	0.9879050	0.9926442
0.9978619	0.9999691	1.0004203	1.0018382	1.0000875	0.9996197
1.017216	0.9977500	0.9992849	0.9833765	1.002165	1.0006942
1.0369239	0.9979938	0.9992997	0.9652372	1.00188	1.0006609
1.0569952	0.9986415	0.9995117	0.9474332	1.0012521	1.0004506

Table 5 - The ratios described in the text for Fre

02./0.5			**0.8/0.5**		
M	**T**	**P**	**M**	**T**	**P**
0.9647200	1.0598867	1.0600997	1.0398087	0.9427753	0.9392572
0.9815760	1.01085	1.0065507	1.0206443	0.9894452	0.9935589
0.9987233	0.9997992	1.0003034	1.0018382	1.000242	0.9997277
1.0161675	0.9978976	0.9993239	0.9833765	1.0020308	1.0006566
1.0339109	0.9981620	0.9994398	0.9652372	1.001737	1.0006106
1.0520056	0.9987602	0.9995548	0.9474332	1.0011457	1.0004143

Table 6 - The ratios between the homologous parameters of the "stands 0.8 and 0.2"

Qro			**Fex**		
M	**T**	**P**	**M**	**T**	**P**
1.0828288	0.8764170	0.8726005	1.0732095	0.8895057	0.8860084
1.0426613	0.9757173	0.9852614	1.0371658	0.9788249	0.9870928
1.0039848	1.0001184	0.9991998	1.0023334	1.0004429	0.9994245
0.9667332	1.004425	1.0014103	0.9686792	1.0041419	1.0013335
0.9308660	1.0038941	1.0013621	0.9361326	1.0035816	1.0011714
0.8963457	1.0026141	1.0009394	0.9047173	1.0023884	1.0008599

I may admit that the figures displayed in tables 4, 5, and 6 corroborate my basic tenant. The values are very close to one and much smaller then the relative changes in the proportions of the species.

In BARRETO (2003b), I also present simulations with stochastic recruitment, of this European MUNF.

The North-American MUNF

In this section I deal with Forest 2, described in table 2.

After the application of step 3, of figure 4, I fitted the equations described in table 7. The Gompertz models virtually reproduce the data generated by model BACO2.

Table 7 - Gomperz equations fitted to the time series of the densities of self-thinned even-aged mixed stands, with fractions of species at age 10 indicated in column Fraction. Sim.=Simulation number; mre=mean of the relative error of the simulations ((value given by the Gompertz equation-value obtained with model BACO2)/value obtained with model BACO2)

Sim.	Species	Fraction	c_i	R_{i-2}	mre
1	Psi	1/3	0.0446087	63.702993	- 0.0013212
	Pme	1/3	0.0449149	63.711538	- 0.0011861
	The	1/3	0.0428964	63.150943	- 0.0016437
2	Psi	0.6	0.0381111	70.675542	0.0272698
	Pme	0.2	0.0466647	61.8125	- 0.0008164
	The	0.2	0.0452232	60.363636	- 0.0011145
3	Psi	0.2	0.0449221	66.000002	- 0.0012337
	Pme	0.6	0.0453120	65.274365	- 0.0011596
	The	0.2	0.0419151	65.032258	- 0.0018562
4	Psi	0.2	0.0439231	62.6875	- 0.0012126
	Pme	0.2	0.0428608	64.709677	- 0.0016657
	The	0.6	0.0414347	65.068296	- 0.0020750
5	Psi	0.4	0.0451255	63.03171	- 0.0011829
	Pme	0.3	0.0451927	63.361702	- 0.0011379
	The	0.3	0.0432867	62.624997	- 0.0015709
6	Psi	0.3	0.0454588	63.382979	- 0.0010439
	Pme	0.4	0.0450291	64.064516	- 0.0011791
	The	0.3	0.0422160	64.148253	- 0.0019033
7	Psi	0.3	0.0442864	63.595741	- 0.0013553
	Pme	0.3	0.0446717	63.574468	- 0.0011866
	The	0.4	0.0423691	63.809016	- 0.0018435
8	Psi	0.5	0.0460257	61.9375	- 0.0009791
	Pme	0.25	0.0450504	63.512008	- 0.0012107
	The	0.25	0.0447204	60.902439	- 0.0011467
9	Psi	0.25	0.0447203	65.146776	- 0.0015007
	Pme	0.5	0.0453815	64.376623	- 0.0011042
	The	0.25	0.0421220	64.512821	- 0.0018625
10	Psi	0.25	0.0432223	64.16101	- 0.0014090
	Pme	0.25	0.0438088	64.076923	- 0.0013912
	The	0.5	0.0330517	78.051254	0.0409162

I used simulations 1 to 4 to accomplish step 4, for a periodicity of five years. I simulated stands with ages from 10 to 399 years, with age classes of 50 years, to generate a parsimonious volume of data, capable of being displayed in a paper. The values obtained are exhibited in tables 8 to 10.

Table 8 - The parameters of the dynamics of Psi in MUNF symmetric to the self-thinned mixed even-aged stands of simulations 1 to 4, in table 7, for a periodicity of five years

Simulation 1			Simulation 2		
M	**T**	**P**	**M**	**T**	**P**
0.3106234	0.0531568	0.6362199	0.3189532	0.0579127	0.6231340
0.0333863	0.0993719	0.8672418	0.0474411	0.0994947	0.8530642
0.0035884	0.0999955	0.8964160	0.0070564	0.1000804	0.8928632
0.0003857	0.1000002	0.8996141	0.0010496	0.1000153	0.8989351
0.0000415	0.1000000	0.8999585	0.0001561	0.1000023	0.8998415
0.0000045	0.1	0.8999955	0.0000232	0.1000004	0.8999764
Simulation 3			**Simulation 4**		
0.3130599	0.0523112	0.6346288	0.309827	0.0540235	0.6361495
0.0331250	0.0993557	0.8675193	0.0344621	0.0993893	0.8661487
0.0035050	0.0999933	0.8965017	0.0038332	0.1000007	0.8961661
0.0003709	0.1000000	0.8996292	0.0004264	0.1000009	0.8995727
0.0000392	0.1	0.8999608	0.0000474	0.1000001	0.8999525
0.0000042	0.1	0.8999958	0.0000053	0.1000000	0.8999947

Table 9 - The parameters of the dynamics of Pme in MUNF symmetric to the self-thinned mixed even-aged stands of simulations 1 to 4, in table 7, for a periodicity of five years

Simulation 1			Simulation 2		
M	**T**	**P**	**M**	**T**	**P**
0.3104281	0.0528875	0.6366844	0.3067368	0.0519070	0.6413562
0.0328584	0.0993667	0.8677749	0.0297478	0.0993505	0.8709017
0.0034780	0.0999935	0.8965285	0.0028850	0.0999839	0.8971311
0.0003681	0.1000000	0.8996319	0.0002798	0.0999989	0.8997213
0.0000390	0.1	0.8999610	0.0000271	0.0999999	0.8999730
0.0000041	0.1	0.8999959	0.0000026	0.1000000	0.8999974
Simulation 3			**Simulation 4**		
0.3119497	0.0521528	0.6358975	0.3126863	0.0544837	0.6328300
0.0323703	0.0993530	0.8682766	0.0366774	0.0994002	0.8639224
0.0033590	0.0999909	0.8966501	0.0043022	0.1000100	0.8956878
0.0003486	0.0999997	0.8996518	0.0005046	0.1000023	0.8994931
0.0000362	0.1000000	0.8999639	0.0000592	0.1000003	0.8999405
0.0000038	0.1000000	0.8999962	0.0000069	0.1000000	0.8999930

Table 10 - The parameters of the dynamics of The in MUNF symmetric to the self-thinned mixed even-aged stands of simulations 1 to 4, in table 7, for a periodicity of five years

Simulation 1			Simulation 2		
M	**T**	**P**	**M**	**T**	**P**
0.3108449	0.0548406	0.6343145	0.3061763	0.0534985	0.6403252
0.0363966	0.0994075	0.8641959	0.0319126	0.0993782	0.8687092
0.0042616	0.1000097	0.8957287	0.0033262	0.0999917	0.8966821
0.0004990	0.1000022	0.8994988	0.0003467	0.0999997	0.8996536
0.0000584	0.1000003	0.8999413	0.0000361	0.1000000	0.8999639
0.0000068	0.1000000	0.8999931	0.0000038	0.1000000	0.8999962
Simulation 3			**Simulation 4**		
0.3133280	0.0552986	0.6313734	0.3134455	0.0557550	0.6307995
0.0385322	0.0994196	0.8620482	0.0394838	0.0994310	0.8610852
0.0047386	0.1000200	0.8952414	0.0049737	0.1000257	0.8950007
0.0005827	0.1000038	0.8994135	0.0006265	0.1000047	0.8993687
0.0000717	0.1000005	0.8999278	0.0000789	0.1000006	0.8999205
0.0000088	0.1000001	0.8999911	0.0000099	0.1000001	0.8999900

Now, it is time to accomplish step 5. I divided the homologous parameters of simulations 2 to 4 by the parameters of simulation 1. The values are displayed in tables 11 to 13.

Table 11 - The ratios described in the text for Psi

	Age classes					
	I	**II**	**III**	**IV**	**V**	**VI**
Simulation 2/Simulation 1						
M	1.0268164	1.4209751	1.9664474	2.721286	3.7614458	5.1555556
T	1.0894693	1.0012358	1.000849	1.000151	1.000023	1.000004
P	0.9794318	0.9836521	0.9960367	0.9992452	0.9998700	0.9999788
Simulation 3/Simulation 1						
M	1.0078439	0.9921734	0.9767584	0.9616282	0.9445783	0.9333333
T	0.9840923	0.9998370	0.999978	0.999998	1.	1.
P	0.9974991	1.00032	1.0000956	1.0000168	1.0000026	1.0000003
Simulation 4/Simulation 1						
M	0.9974361	1.0322228	1.0682198	1.1055224	1.1421687	1.1777778
T	1.0163046	1.0001751	1.000052	1.000007	1.000001	1.
P	0.9998893	0.9987396	0.9997212	0.9999540	0.9999933	0.9999991

The values relative to mortality, for more advanced ages (after age class II), reflect computational errors generated by manipulation of numbers very close to zero. Remember figure 3. In Leslie models the parameters used are T, and P, as known. Also, values of M close to zero are irrelevant for modelling purposes.

The figures in tables 11 to 13 also corroborate my basic hypothesis.

In BARRETO (2003c), I analysed MUNF of Pme, Psi, and *Alnus rubra.*

For North-American species, in BARRETO (1999) I already presented a simulator for even-aged stands, pure, and mixed.

Table 12 - The ratios described in the text for Pme

	Age classes					
	I	**II**	**III**	**IV**	**V**	**VI**
Simulation 2/Simulation 1						
M	0.988109	0.9053332	0.8294997	0.7601195	0.6948718	0.6341463
T	0.9814606	0.9998370	0.9999040	0.999989	0.999999	1.
P	1.0073377	1.0036032	1.0006721	1.0000994	1.0000133	1.0000017
Simulation 3/Simulation 1						
M	1.0049016	0.9851454	0.9657849	0.9470253	0.9282051	0.9268293
T	0.9861082	0.9998621	0.999974	0.999997	1.	1.
P	0.9987641	1.0005781	1.0001356	1.0000221	1.0000032	1.0000003
Simulation 4/Simulation 1						
M	1.0072745	1.116226	1.2369753	1.3708231	1.5179487	1.6829268
T	1.030181	1.0003371	1.000165	1.000023	1.000003	1.
P	0.9939461	0.9955605	0.9990623	0.9998457	0.9999772	0.9999968

Table 13 - The ratios described in the text for The

	Age classes					
	I	**II**	**III**	**IV**	**V**	**VI**
Simulation 2/Simulation 1						
M	0.9849809	0.8768017	0.7805050	0.6947896	0.6181507	0.5588235
T	0.9755273	0.9997053	0.9998200	0.999975	0.999997	1.
P	1.0094759	1.0052225	1.0010644	1.0001721	1.0000251	1.0000034
Simulation 3/Simulation 1						
M	1.0079882	1.0586758	1.1119298	1.1677355	1.2277397	1.2941176
T	1.0083515	1.0001217	1.000103	1.000016	1.000002	1.000001
P	0.9953633	0.9975148	0.9994560	0.9999052	0.999985	0.9999978
Simulation 4/Simulation 1						
M	1.0083662	1.0848211	1.1670969	1.255511	1.3510274	1.4558824
T	1.0166738	1.0002364	1.00016	1.000025	1.000003	1.000001
P	0.9944586	0.9964005	0.9991873	0.9998554	0.9999769	0.9999966

An Illustrative Model

For the sake of completeness, let me use the information already presented to establish a model for the North-American MUNF.

In my hypothetical MUNF, I used the values of simulations 1, in tables 8 to 10 to establish the matrix model of the MUNF, with Psi (matrix S), Pme (matrix M), and The (matrix H), displayed as eqs. (11) to (13). I simulate a stand with initial values only in the first age class. Psi with 10^6 trees, Pme with 10^5, The with 10^4. After 60 projections (300 years) the structure of the MUNF is described in table 14, and illustrated in figure 5.

$$S=\begin{bmatrix} 0.3 & 0.37 & 0.387 & 0.387 & 0.37 & 0.3 \\ 0.0531568 & 0.8672418 & 0 & 0 & 0 & 0 \\ 0 & 0.0993719 & 0.896416 & 0 & 0 & 0 \\ 0 & 0 & 0.0999955 & 0.8996141 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0.8999585 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0.8999585 \end{bmatrix} \qquad (11)$$

Dominant eigenvalue : 1.0000562

$$M=\begin{bmatrix} 0.3 & 0.37 & 0.387 & 0.387 & 0.37 & 0.3 \\ 0.0528875 & 0.8677749 & 0 & 0 & 0 & 0 \\ 0 & 0.0993667 & 0.8965285 & 0 & 0 & 0 \\ 0 & 0 & 0.0999935 & 0.8996319 & 0 & 0 \\ 0 & 0 & 0 & 0.1 & 0.8999610 & 0 \\ 0 & 0 & 0 & 0 & 0.1 & 0.8999959 \end{bmatrix} \qquad (12)$$

Dominant eigenvalue : 1.0000533

$$H=\begin{bmatrix} 0.3 & 0.375 & 0.386 & 0.386 & 0.36 & 0.3 \\ 0.0548406 & 0.8641959 & 0 & 0 & 0 & 0 \\ 0 & 0.0994075 & 0.8957289 & 0 & 0 & 0 \\ 0 & 0 & 0.1000097 & 0.8994988 & 0 & 0 \\ 0 & 0 & 0 & 0.1000022 & 0.8999413 & 0 \\ 0 & 0 & 0 & 0 & 0.1000003 & 0.8999931 \end{bmatrix} \qquad (13)$$

Dominant eigenvalue : 1.0000321

Table 14 - The initial and final structures of the MUNF, after 300 years of simulation

Classes	Psi		Pme		The	
	Initial	Final	Initial	Final	Initial	Final
I	10^6	45548	10^5	5129	10^4	455
II	0	18385	0	2046	0	184
III	0	17751	0	1951	0	175
IV	0	17986	0	1949	0	174
V	0	18518	0	1977	0	174
VI	0	18721	0	1971	0	173

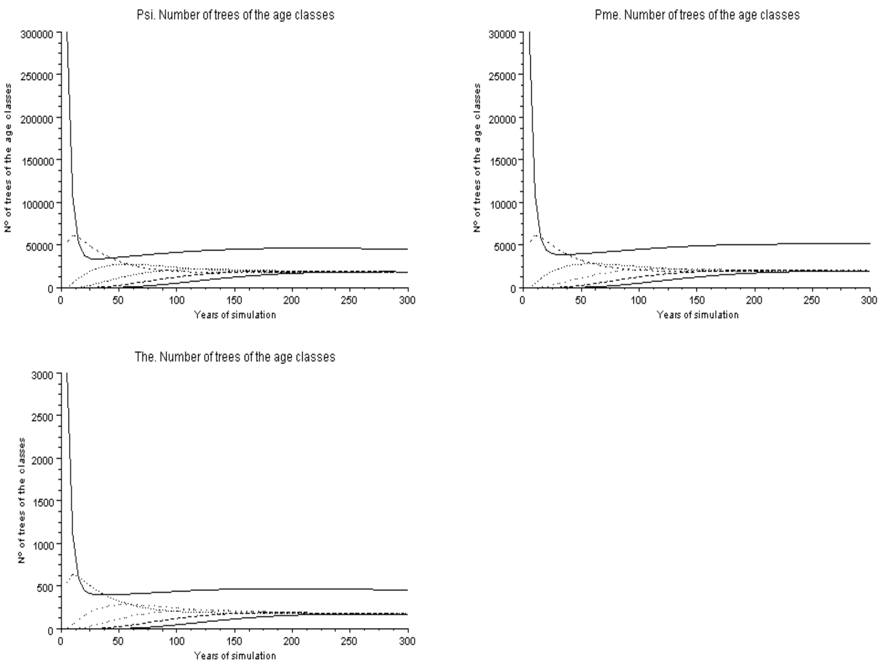

Figure 5 - Deterministic simulation with the model of eqs. (11) to (13). See text for details

The simulation corroborates the close competitiveness of the three species, as expected.

In nature, given the competitive hierarchies already described, in the long range, it is highly probable that The will be the more abundant specie of the

MUNF, as already depicted by LIANG, BUONGIORNO, and MONSERUD (2005), and Psi the less abundant specie.

Stochasticity can be introduced into the model, in the more convenient way, according to the purpose of the simulations.

Related Issues

Let me approach two aspects that deserve mention.

If the information is available, and a very intensive extraction is executed from the MUNF, as for mixed even-aged stands (Barreto, Forthcoming), method SB-BARTHIN can be applied to the stand. It is only a matter of computer programming, for instance, when applying the procedure described in the next section.

The other aspect is the inclusion of dbh classes in MUNF. To clarify this issue, I use a numerical example, of a pure hypothetical situation.

Let us consider the population of a MUNF, with three age classes and the following matrix model A:

$$A = \begin{bmatrix} 0.1 & 0.3 & 04 \\ 0.1 & 0.2 & 0 \\ 0 & 0.7 & 0.5 \end{bmatrix} \tag{14}$$

The frequencies of the age classes are the following one:

$$n=[24\ 15\ 6]' \tag{15}$$

Each age class has three dbh classes: small, average, large. I assume that in the next period of projection, the trees in a given dbh class of age class j, moves to the homologous dbh class of age class j+1. The vector of the frequencies of the disaggregated structure is:

$$n_d=[9\ 8\ 7\ 6\ 5\ 4\ 3\ 2\ 1]' \tag{16}$$

Now the transition matrix B is:

$$B=\begin{bmatrix} 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.3 & 03 & 03 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.4 & 0.4 & 0.4 \\ 0.1 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 & 0.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1 & 0 & 0 & 0.2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 07 & 0 & 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.7 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.7 & 0 & 0 & 0.5 \end{bmatrix} \tag{17}$$

To obtain matrix B, from matrix A, in Scilab or Matlab, use the following commands:

```
m11=[A(1,1)*ones(1,3);zeros(2,3)];
m12=[zeros(1,3);A(1,2)*ones(1,3);zeros(1,3)];
m13=[zeros(2,3);A(1,3)*ones(1,3)];

e=eye(3,3);
m21=A(2,1)*e;m22=A(2,2)*e;m23=zeros(3,3);
m31=zeros(3,3);m32=A(3,2)*e;m33=A(3,3)*e;

B=[m11 m12 m13;
   m21 m22 m23;
   m31 m32 m33];
```

An Alternative Approach to Simulate Mixed Uneven-Aged Forests

In this section I simulate Forest 3, described in table 2.

A method that can be applied to man-made or natural mixed uneven-aged forests is to consider each age of each species as distinct specie, in an even-aged stand, and apply model BACO2. Taking advantage of the capacity of Scilab (or Matlab) to deal with vectors, a very compact, but clear program can be written, with less then 50 lines. The recruitment can be easily introduced, deterministic, or stochastic, as desired. In this approach values of M, T, and P, are unnecessary. The program produces the complete structure of each species every year. Also, various levels of detail and criteria, to classify the trees of each age, can be adopted.

In figure 7, I present the output of a simulator established as described in the precedent paragraph. The simulated forest has two r-3 strategists: *Pinus pinaster*, and *Betula pendula*, also characterized in table 2. I consider the frequencies of ages 11 to 61. The per capita rates of mortality of these two species are exhibited in figure 6. The annual recruitment is given by two stochastic variables with N(1000,50). The simulation ran for 150 years.

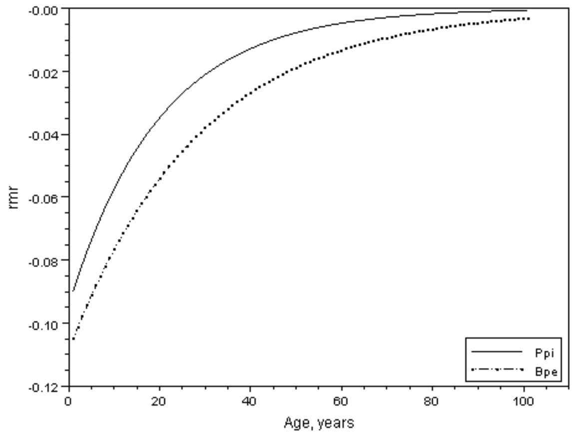

Figure 6 - The per capita rates of mortality (rmr) of *Betula pendula* (Bpe), and *Pinus pinaster* (Ppi)

For Excel, in Software SB-ROBLE (BARRETO, 2004c) I already disclosed simulators for even-aged mixed stands that also estimated the values of M, T, P, for the following stands with *Q. robur*: *Q. robur* + *Abies alba*; *Q. robur* + *Acer pseudoplatanus*; *Q. robur* + *Betula pendula*; *Q. robur* + *Fraxinus excelsior*; *Q. robur* + *Fagus sylvatica*; *Q. robur* + *Larix decidua*; *Q. robur* + *Pinus nigra* ssp. *Laricio*; *Q. robur* + *Pinus sylvestris*; *Q. robur* + *Acer pseudoplatanus* + *Fagus sylvatica*; *Q. robur* + *Acer pseudoplatanus* + *Fraxinus excelsior*; *Q. robur* + *Fagus sylvatica* + *Fraxinus excelsior*; *Q. robur* + *Larix decidua*+ *Fraxinus excelsior*; *Q. robur* + *Acer pseudoplatanus* + *Fraxinus excelsior*; *Q. robur* + *Pinus sylvestris* + *Fraxinus excelsior*

At the same time, in Software SB-BRAMIX (BARRETO, 2004c) I also made available seven simulators for even-aged mixed stands with *Pinus pinaster* and one species, and three simulators for this pine and two more species, that calculate M, T, P, for the species of the mixture. All species in these ten simulators are r-strategists. The models in these two softwares, for the mixed uneven-aged stands, indicate the number of trees to be extracted, every five years.

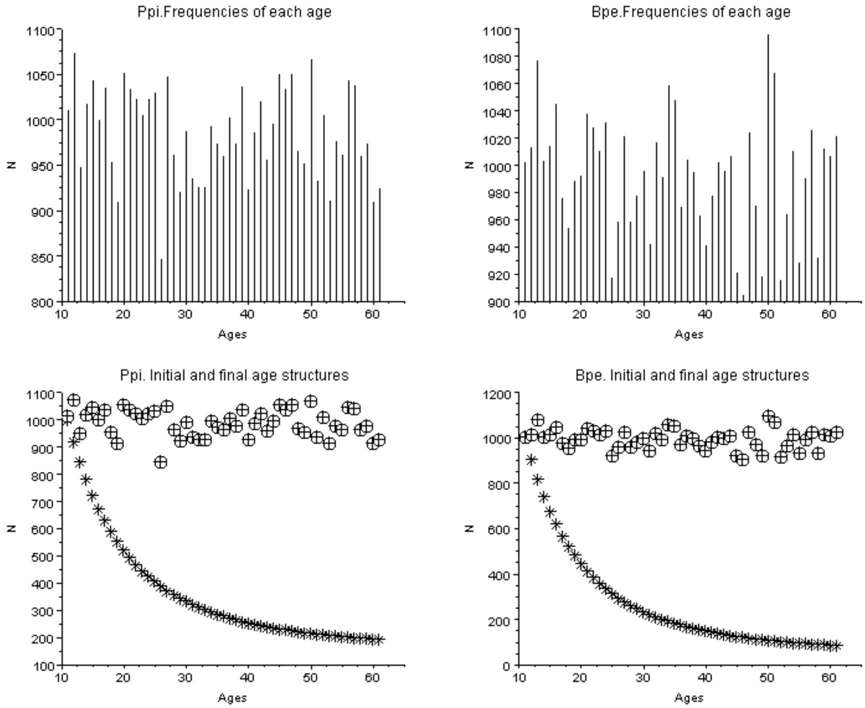

Figure 7 - The simulation of a mixed uneven-aged forest with *Pinus pinaster* (Ppi), and *Betula pendula* (Bpe), considering each age as a specie in a even-aged stand. Initial structure represented by asterisks. For more details see the text

Conclusive Comments

The corroboration of my basic assumption, brings the management of MUNF to the arena of sound ecological theory, and opens new perspectives to their forestry. Confirming its fecundity, my theory generated two alternative approaches to the modelling of mixed uneven-aged forests: a discrete, and a continuous one.

The possibility of using matrix population models in the management of MUNF is relevant, and reinforces an approach that lasts for more then forty years, since the seminal paper by USHER (1966). Thus, a credible alternative to the regressive approach, reified in the individual tree models, can be developed on robust theoretical grounds, as the matrix population models form a subject that is very well developed, and established (e.g., CASWELL, 2001). They are intelligible, their interpretation is clear, and they can bring practical and analytical benefits to the management of MUNF, even to forests in danger of disappearance (conservation and protection).

We can establish a matrix model assuming a balanced structure of the symmetric even-aged stand, and apply it to the MUNF. Assuming a stable age structure, the first line of the Leslie model (recruitment) can be established analytically, and latter be submitted to a progressive process of improvement, if necessary. Given the light exploitation of the MUNF, in the new paradigm of forest management, the risk of the inadequacy of the model is minimal.

Matrix models are also easily incorporated in information systems, and decision support systems for multi-criteria forest planning and management.

The availability of the parameters M, T, P creates the possibility for the use of other modelling approaches, such as the model of BUONGIORNO and MICHIE (1980), and differential equations (BARRETO, 2002).

The continuous modelling approach brings the management of mixed uneven-aged stands to the more tractable territory of mixed even-aged stands (Barreto, forthcoming).

This paper also evinces the advantages of having a unified and coherent theory for pure, and mixed, even, and uneven-aged stands.

An open issue is if the generalized adoption of forestry for MUNF does not lead to a landscape dominated by climax forests, where r, r↔K, and some K-1 strategists can not be easily accommodated (e.g., SPIECKER, 2006). In a long term, biodiversity can be impoverished if the future of this species is not carefully forecasted, monitored, and adequate measures are not implemented, to guarantee their persistence.

Another aspect that is beyond the scope of this paper is if the new paradigm for forestry (MUNF lightly exploited) is the best strategy at the **planet** scale, given the increasing demand of wood, conspicuously accelerated by the expansion of the emergent economies.

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Entregue para publicação em outubro de 2007
Aceite para publicação em fevereiro de 2017

Silva Lusitana, **25**(1): 107 - 108, 2017

Notícia

Feira Ligna Hannover 2017

Realizou-se entre 22 e 26 de Maio de 2017, mais uma edição da LIGNA, a maior feira mundial da Indústria e conversão de madeira, em Hannover, na Alemanha. O evento ocorreu no Hannover Exhibition Center e foi organizado pela Deutche Messe AG, empresa proprietária e operadora do Hannover Exhibition Center. Realizada com periodicidade bienal, a LIGNA em 2017 contou com uma presença de mais de 1500 expositores, provenientes de 40 países e de 93000 visitantes, numa área de 120000 m^2, tendo sido dinamizados cerca de 2.8 milhões de contactos entre os visitantes e expositores no período de 5 dias. Este evento é de relevante interesse para Portugal, dada a posição económica do sector florestal nacional. Particularmente significativa foi a Wood Industry Summit (WIS), no Pavilhão 26, considerada como a primeira plataforma mundial de encontro de todos os sectores da indústria do cluster primário florestal, envolvendo as tecnologias de exploração e conversão energética. Nesta plataforma, que teve início na LIGNA 2015, com um volume de projetos de investimento contratados de 30 milhões de Euros, foram apresentadas soluções inovadoras para o abate e processamento e para integração das várias fases de processamento da madeira. O WIS 2017, foi focalizado num tópico por cada dia entre 22 e 26 de Maio de interesse primordial para a indústria global. Neste contexto os temas da WIS cada dia do evento foram: o papel das indústrias de exploração florestal e de madeiras no regime geral de alterações climáticas, a visão Forest 4.0, as infraestruturas florestais, o combate aos fogos florestais e a otimização da cadeia logística da floresta à indústria.

Para apresentação da LIGNA 2017 realizou-se a Conferência Ligna Preview 2017 a 14 de Fevereiro último, em que quatro oradores apresentaram algumas linhas gerais da feira. Para este evento, que contou com mais de duzentos participantes provenientes de 25 países, foi convidada a Revista Silva Lusitana que se fez representar pelo signatário. As intervenções focalizaram os objetivos de descrição do programa e infraestrutura da LIGNA 2017, a caracterização da situação da economia mundial do setor de equipamento de indústrias de madeira e a análise do impacto da digitalização e da tecnologia 4D no design de produtos e equipamentos para a indústria de madeira. A dinâmica da digitalização induzirá inovação na produtividade, flexibilidade e conceptualização de novos produtos de madeira e derivados. O orador Giulio Masotti apresentou o produto digital Wood-Skin™ da empresa startup Wood-Skin Srls de fabrico digital, resultante de um processo de investigação aplicada sobre geometrias complexas e tecnologia de materiais. Este produto é um resultado de um trabalho der investigação sobre processos de fabrico digitais e soluções inovadoras para materiais, incluindo a madeira. A empresa Wood-Skin Srls desenvolveu competências em arquitetura e projetos de design, investigação e inovação em novos materiais, tecnologias interativas, fabrico por digitalização e design informático. Foi também particularmente interessante o contacto com a tecnologia de scanning, comercializada pela empresa italiana MICROTEC, para a otimização do corte das pranchas de madeira.

Estiveram representadas na Ligna 2017, empresas dos diversos sectores da indústria de madeira, nomeadamente equipamento de exploração florestal, serração, materiais compósitos derivados de madeira, equipamentos, habitação em madeira ou conversão energética da biomassa. Na Ligna 2017 os países com maior presença de expositores foram, por ordem decrescente, a Alemanha, Itália, Áustria, Espanha, Turquia, Dinamarca, China, Suécia, Holanda e Suíça. A origem dos visitantes perfilou-se maioritariamente pela Europa (71%), Américas (12%), Ásia (11%), Austrália (4%) and África (3%). Os expositores nacionais foram as sete empresas seguintes: Ventilações Moura Lda., Advanced Cyclone Systems, Torbel S.A., Ventil Engenharia do Ambiente Lda., Silvino Lindo Iberica S.A., AFICOR Ferramentas de Corte Lda., e Frezite–Ferramentas de Corte Lda, com produtos de aplicação às indústrias de madeira como sejam discos de serra, fitas de serra, silos, sistemas de filtragem ou caldeiras. O site da Ligna Hannover http://www.ligna.de/home contém uma descrição pormenorizada do evento.

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IINIAV, I.P.

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Índice do Volume 24 (2016)

Nº 1/2, Dezembro de 2016

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2017, Vol. 25(1) : 1 - 112

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