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O Desafio da Preservação dos Solos

Hélder Muteia

Nas últimas décadas, o número de pessoas que passam fome no planeta reduziu significativamente. Contudo, e segundo os dados divulgados em 2015 pela Organização das Nações Unidas para a Alimentação e a Agricultura (FAO), cerca de 795 milhões de pessoas ainda sofrem deste mal (FAO, 2015), ou seja, uma em cada nove pessoas no mundo.

As projeções para 2050 indicam uma população mundial de cerca de 9,3 mil milhões de pessoas (UNITED NATIONS, 2011), devendo as necessidades em cereais aumentar dos atuais 2,4 para os 3 milhões de toneladas e as necessidades de carne dos atuais 270 para 450 milhões de toneladas. Isso implica um aumento de cerca 60% na produção agroalimentar (ALEXANDRATOS, N., e BRUINSMA, J., 2012), perante apenas 20% de potencial de expansão sustentável dos solos agrícolas (FAO, 2015a).

Num passado recente, a abordagem da problemática alimentar era baseada em modelos muito simplificados, levando em consideração, essencialmente, 4 elementos: a disponibilidade de alimentos, como função da produção; o acesso, refletido no rendimento individual e familiar; a utilização, na vertente nutricional; e a estabilidade, muitas vezes influenciada por fatores climáticos e logísticos.

Ao longo de muito tempo esta abordagem revelou-se adequada aos processos de avaliação da situação de segurança alimentar e nutricional, identificação dos elementos críticos e prioritários, elaboração de políticas e

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estratégias, bem como na planificação de programas, projetos e atividades diversas ao longo da cadeia de valor dos alimentos.

Na sequência do surgimento de novos fenómenos, fatores e desafios sociais, tecnológicos, ambientais e económicos, houve a necessidade de adotar modelos mais complexos e que permitissem incorporar um número crescente de indicadores e elementos de análise essenciais.

Entre eles destacam-se os aspetos ambientais, relacionados com a base de recursos naturais que permite a produção primária dos alimentos, o alargamento da cadeia de valor dos mesmos, a explosão demográfica (e outros fenómenos relacionados, como a urbanização e o envelhecimento demográfico), o conjunto de novas realidades culturais e sociais, os diferentes aspetos ligados à governança e políticas, as relações geopolíticas, etc.

Os sistemas alimentares modernos

Da análise dos sistemas alimentares modernos, cada vez mais dinâmicos e complexos, sobressaem algumas realidades preocupantes, como a paradoxal coexistência do crescente aumento da disponibilidade de alimentos e dos números assustadores da prevalência da fome.

Outro tema preocupante é o agravamento do desperdício de alimentos, que acontece ao longo de toda a cadeia de valor e nas mais variadas realidades socioeconómicas e geográficas. Estima-se que 1/3 da produção total é perdida ou desperdiçada.

Não menos relevante é a abordagem da crescente pressão exercida sobre os recursos naturais, particularmente os solos, a água, a floresta e a fauna.

Os solos, em particular, têm merecido uma atenção especial, partindo da consciência de que estão cada vez mais degradados e mais escassos. Embora represente apenas ¼ da superfície do planeta, a crosta terreste é fundamental para a vida. Por isso, a crescente degradação dos solos deve ser uma das maiores preocupações da humanidade. Nos últimos 40 anos, cerca de 33% dos solos foram degradados (25% muito degradados e 8% moderadamente degradados) como resultado de vários fatores relacionados com a urbanização, sobre-exploração, sobre-pastoreiro, alterações climáticas, poluição, desertificação, salinização e desflorestação. (FAO, 2015b).

A degradação (física, química e biológica) dos solos teve também efeitos na redução da cobertura vegetal, na diminuição da biodiversidade e na poluição e escassez da água. Sabe-se que a recuperação do equilíbrio entre os vários elementos da base de recursos naturais, quando possível, é um processo muito lento. Por isso, os solos são considerados recursos não renováveis.

Fica evidente que a forma como vivemos, produzimos e utilizamos os recursos naturais, incluindo a terra e os solos, conduz a humanidade para uma situação de crise iminente nos sistemas alimentares, com efeitos na sustentabilidade ambiental, volatilidade dos preços dos alimentos, eficiência dos mercados agrícolas e estabilidade social.

Esta situação pode, por sua vez, conduzir à pobreza e à dificuldade de acesso a terras e recursos hídricos em alguns países e grupos sociais. Estudos recentes demonstram que os agricultores mais pobres têm cada vez maiores dificuldades de acesso à terra e à água, sendo obrigados a cultivar em solos empobrecidos e muito vulneráveis à degradação. Cerca 40% das terras mais degradadas ficam em áreas com elevados níveis de pobreza (FAO, 2011).

O desafio da sustentabilidade

Há claras evidências de que, ao longo da sua história de desenvolvimento, a humanidade descurou de alguns elementos relacionados com a sustentabilidade ambiental e social. O entusiamo gerado pelos sucessos da revolução industrial e da revolução verde induziram a certos equívocos que urge contextualizar e solucionar.

Só muito recentemente se ganhou consciência da necessidade de reverter a degradação dos solos, como forma de garantir o equilíbrio ecológico, a manutenção da biodiversidade e dos ecossistemas, a regulação do ciclo da água e do carbono, a prevenção de cheias, secas e outras catástrofes naturais.

Os solos albergam uma grande variedade de microrganismos, particularmente bactérias e fungos. Um grama de terra pode conter milhares de espécies bacterianas (FAO, 2015c).

Desempenham ainda funções de suporte físico e químico para diversas formas de vida, pois sustentam uma extensa e rica cobertura vegetal e albergam ainda diferentes formas de vida animal (nematoides, artrópodes, protozoários, pássaros, pequenos mamíferos, répteis etc.). Estima-se que um m^2 de solo florestal contenha mais de mil espécies de seres invertebrados (FAO, 2015a).

Constituem, assim, um sistema vivo e dinâmico que intervém como regulador dos ciclos biogeoquímicos e hidrológicos, funcionando como filtro e reservatório de água e matéria orgânica e, ainda, como tampão face a diversos riscos de contaminação ambiental (ABREU, M., e CORTEZ, N., 2008).

A degradação dos solos põe em risco essas funções vitais do solo, nomeadamente, a produção de biomassa, o armazenamento de nutrientes, água e dióxido de carbono, a manutenção da biodiversidade e a disponibilização de recursos naturais. (FAO, 2015a).

Solos saudáveis para uma agricultura sustentável

A degradação dos solos não afeta apenas a o equilíbrio ecológico. Afeta particularmente a agricultura e a produção sustentável de alimentos. Sabe-se que 95% da produção alimentar é feita com recurso aos solos (ALEXANDRATOS, N., e BRUINSMA, J., 2012).

Estudos recentes da FAO demonstram que uma gestão sustentável e cuidada dos solos pode aumentar em 58% a produção alimentar. A promoção das boas práticas, como o plantio direto, a lavoura mínima, a agroecologia, a agricultura biológica e de conservação, os sistemas agroflorestais e a agricultura inteligente face ao clima, podem promover o aumento da produtividade sem prejudicar os solos.

Perante esta realidade, o ano de 2015, foi designado o Ano Internacional dos Solos, para sensibilizar a sociedade civil, o público e os decisores políticos sobre o tema, despertar consciências, promover iniciativas, incentivar políticas, programas, projetos e ações no sentido da manutenção e preservação deste recurso.

É sobretudo crucial alterar paradigmas, através da adoção de políticas públicas e iniciativas de cooperação e colaboração entre países e povos relativamente à preservação de ecossistemas e, ainda, a sensibilização dos demais atores para a importância de uma relação sustentável com os solos.

As medidas gerais devem incluir a planificação urbana e o melhoramento do ordenamento territorial, a promoção de atividades de pesquisa sobre os solos, a partilha sistematizada de conhecimentos e informação tecnológica sobre solos, a atribuição de valores económicos aos serviços e danos aos ecossistemas, o desenvolvimento de políticas inovadoras para o uso e aproveitamento de terras, e o estímulo à manutenção da cobertura vegetal dos solos.

Como medidas específicas para sector agrário apela-se ao combate à erosão, através de práticas agrícolas adequadas, à promoção da rotação e consorciação de culturas, ao estímulo da fertilização natural dos solos com recurso a matéria orgânica, à regulamentação e restrição do uso de fertilizantes químicos, à gestão sustentável da água para a agropecuária, e ao maneio sustentável das pastagens.

Referências bibliográficas

ABREU, M.M., CORTEZ, N., 2008. *Solo – Recurso natural a preservar*. Instituto Superior de Agronomia, Universidade Técnica de Lisboa.

ALEXANDRATOS, N., BRUINSMA, J., 2012. *World agriculture towards 2030/2050: the 2012 revision*. FAO, Rome, 147 pp.

FAO, 2011. *The State of the World's land and water resources for food and agriculture*. Roma

FAO, 2015. *The State of Food Insecurity in the World 2015*, Roma.

FAO, 2015a. http://www.fao.org/3/a-i4551e.pdf, consultado no dia 5 de janeiro 2016.

FAO, 2015b. http://www.fao.org/documents/card/en/c/ec28fc04-3d38-4e35-8d9b-e4427e20a4f7/, consultado no dia 4 de janeiro 2016.

FAO, 2015c. http://www.fao.org/documents/card/en/c/645883cd-ba28-4b16-a7b8-34babbb3c505/ consultado no dia 4 de janeiro 2016.

UNITED NATIONS, 2011. *Seven Billion and Growing: The Role of Population Policy in Achieving Sustainability*, Department of Economic and Social Affairs.

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Enhancing Multispectral Discrimination among Vegetation Types with a New Pseudo-Color Imaging Method

Ryoichi Doi

Abstract. In this study at the Sakaerat Biosphere Reserve of Thailand, 15 derivative grayscale images were generated from grayscale images, for redness and greenness, among 7 Landsat grayscale images. The use of all 22 grayscale images provided an additional principal component and a larger number of pixel clusters. As evergreen forest is the natural vegetation type of Sakaerat, all pixels in the image were grayscaled based on the principal component score as an indicator of the clusters' evergreen forest-likelihood. Using separate sets of the 7 Landsat images and all 22 grayscale images Dunnett's *t*-test completely discriminated values of evergreen forest-likelihood for seven 300 m × 300 m plots with different vegetation types, favored by a difference in the pattern of mean separation between the image sets. With all 22 grayscale images, the evergreen forest plot was more significantly discriminated from that of fire-protected deciduous forest compared to the Landsat images alone. Thus, differences in visible reflectance revealed by the derivative grayscale images quantified the degree of ecological restoration more strictly than the conventional Landsat images. The proposed imaging method would thus improve the real-time observation of forest and other canopies when used together with multispectral sensors.
Key words: Canopy reflectance, deforestation and conservation, Landsat 7, plant communities, remote sensing

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Melhor discriminação multiespectral entre tipos de vegetação: um novo método de composição colorida falsa-cor

Sumário. No estudo da Reserva Mundial da Biosfera de Sakaerat, Tailândia, geraram-se 15 imagens (em tons de cinza) derivadas de 2 imagens de satélite Landstat (em tons de cinza) seccionadas. Ao total das 22 imagens (em tons de cinza) aplicaram-se métodos estatísticos convencionais, como a análise em componentes principais e análise de "clusters". Adicionou-se um novo componente principal e aumentaram-se os "clusters" do "pixel", na procura de combinações que permitissem a classificação da floresta perenifólia, o tipo de floresta natural de Sakaerat. Nos resultados obtidos, os testes de Dunnett permitiram determinar tipos de vegetação estatisticamente diferentes da floresta perenifólia para cada uma das 7-parcelas simuladas, com áreas de 300 m x 300 m. Nas 22-imagens derivadas em tons de cinza, a classificação da área da parcela de floresta narural perenifólia é significativamente distinta da floresta caducifólia (pós-incêndio), de proteção e permitiu a quantificação do grau de restauro ecológico da floresta em Sakaerat. Pode-se concluir que este processamento digital de imagens melhorou a deteção remota, em tempo-real, da floresta efetuada pelos sensores multiespectrais do satélite.
Palavras-chave: Reflectância da copa das árvores, desarborização e conservação, Landsat 7, comunidades vegetais, deteção remota

Amélioration de la discrimination multispectrale des couvertures végétales avec une nouvelle méthode d'imagerie pseudo-couleur

Résumé. Dans cette étude de la réserve de la biosphère de Sakaerat en Thaïlande, 15 images dérivées en niveaux de gris ont été générées à partir d'images du niveau de gris, pour la rougeur, la verdure et le bleu, parmi 2 images Landsat en niveaux de gris. L'exploitation des 22 images en niveau de gris a permis d'avoir une composante principale supplémentaire et un plus grand nombre de groupes de pixels. Etant donné que le type de végétation naturelle de Sakaerat est une forêt à feuilles persistantes, tous les pixels de l'image ont été reproduits en niveau de gris en se basant sur le score de la composante principale comme indicateur des groupes «ressemblance aux forêts feuillus». En utilisant un ensemble distinct de 7 images Landsat et de 22 images du niveau de gris le *t*-test de Dunnett a complètement discriminé les valeurs de ressemblance à une forêt à feuilles persistantes pour sept parcelles de 300 m × 300 m avec différents types de végétations, favorisée par une différence entre l'ensemble des images. Avec les 22 images en niveaux de gris, les placettes de forêt à feuilles persistantes ont été discriminées plus significativement que celles de la forêt feuilles protégées contre les incendies en se basant uniquement sur les images Landsat. Ainsi, la différence pour une réflexion révélée par des images du niveau du gris a quantifié le niveau écologique de restauration qui est plus strict que les images Landsat classiques. La méthode d'imagerie proposée permettrait ainsi d'améliorer l'observation en temps réel de la forêt et d'autres couvertures végétales lorsqu'elles sont utilisées avec des capteurs multispectraux.
Mots-clés: Réflexion de la canopée, déforestation et conservation, Landsat 7, peuplements végétales, télédétection

Introduction

Observation of forest canopies enables the suitable management of forests by detecting changes caused by above-ground stresses (SICHER, 1999), poor soil conditions (OLSZEWSKA *et al.*, 2008), and other problems such as deforestation. The real-time detection of these changes can enable timely measures to solve such problems. Various methods for observation of forest canopies are currently available. For example, unmanned aerial vehicles with sensors are becoming commonly available, thus enabling the real-time detection of changes in the forest canopy profile. Unlike satellites that orbit the Earth and acquire images of each site periodically, the latest devices acquire real-time and more precise images with high spatial resolution, such as one square centimeter per pixel (CHAVES *et al.*, 2015). For the timely observation of forest canopies, multispectral sensors are more feasible in terms of cost (EHSANI *et al*., 2012; DEERY *et al.*, 2014), simplicity, and technical difficulty (NEBIKER *et al.*, 2008; TONG *et al.*, 2014). These multispectral sensors have a disadvantage, however, in that they acquire image data on limited numbers of bands, often around six. A typical sensor's multispectral bands are blue, red, green, near-infrared, and mid-infrared (KRAMER, 2012). This number is relatively small compared to that of the bands of hyperspectral sensors. These smaller band numbers have been recognized to limit their application (MARIOTTO *et al.*, 2013).

This disadvantage could, however, be significantly reduced through a pseudo-color imaging method. This method would generate derivative grayscale images derived from grayscale images acquired by a multispectral sensor (DOI, 2014, Figure 1), and would achieve discrimination among slightly different objects (DOI *et al.*, 2014). Some derivative grayscale images were suggested to extend the dimensionality of changes in the reflectance of objects (DOI, 2014). For example, in Figure 1b, the key black derivative grayscale image generated from the red (R)-green (G)-inverted R-G-blue (B) yellow (RGrgby^{-1}B, Figure 1b) pseudo-color image shows a non-linear pattern against the bright-dark gradients in the red, green, and RGB yellow grayscale images (Figure 1a). In Figure 1a, changes in redness, greenness, and RGB yellowness have linear relationships to one another and are known to describe a large portion of information on the colors of plant organs (MULLA, 2013). Other than these linearly correlated changes, the non-linearity of some derivative grayscale images generated from the pseudo-color models in Figure 1b may exhibit differences that cannot be found through the original multispectral bands.

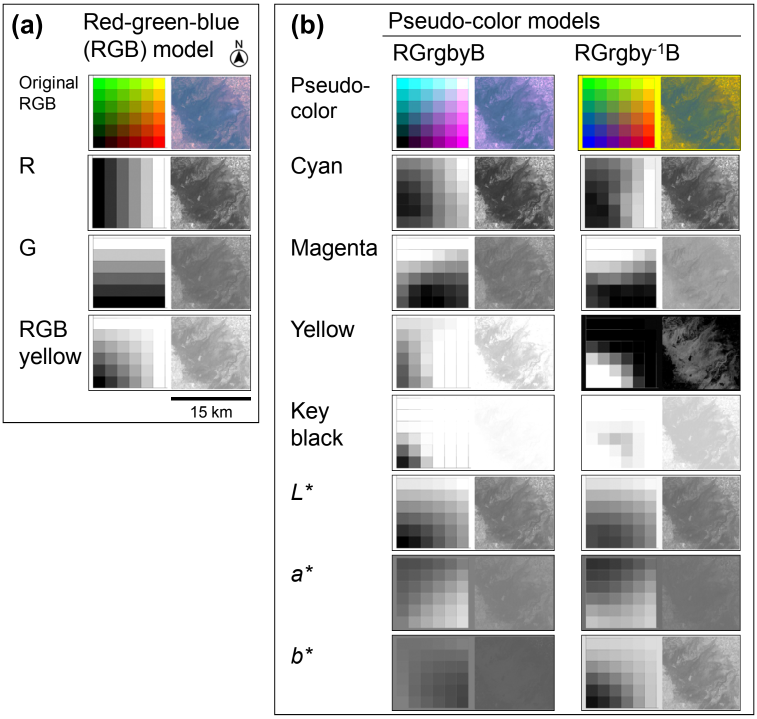

Figure 1 *- Changes in the grayscale intensity of pixels in grayscale images of standard color gradients (left) and Landsat image of Sakaerat (right) in red-green-blue (a) and pseudo-color models (b) investigated in this study*

Against this background, this study was conducted to investigate the pseudo-color method's information additivity that enhances discrimination among pixels in a multispectral Landsat image of the Sakaerat Biosphere Reserve in Thailand. In Sakaerat, the natural vegetation type is tropical evergreen forest. There are other vegetation types that differ in the intensity of deforestation or degree of ecological restoration. Using Landsat images only or all Landsat and derivative grayscale images in Figure 1, pixels representing plots of the vegetation types were evergreen forest-likelihood-scored. For the dataset on the 7 Landsat images and that on the 7 plus 15 derivative grayscale images, statistical analyses were performed to examine if the derivative grayscale images aid in statistical discrimination among the plots by comparing values of evergreen forest-likelihood for the plots.

Methods

Grayscale images acquired by the Landsat 7 satellite were used to generate 15 derivative grayscale images (Figure 1). After running pixel clustering software, the clusters were multivariate-profiled based on values of the grayscale intensity for 1) the original seven Landsat grayscale images and 2) all grayscale images, including the derivative grayscale images from the pseudo-color images (Figure 1b). The most significant principal component was extracted from the clusters' mean grayscale intensity values for the Landsat grayscale images. Based on the principal component scores for the clusters, evergreen forest-likelihood was shown as the grayscale intensity values of pixels belongings to the clusters. Evergreen forest-likelihood was determined for 100 pixels in each of seven plots of different vegetation types that differed in the intensity of deforestation and the degree of ecological restoration. The means of evergreen forest-likelihood for the plots were *t*-tested using the seven Landsat images or both the Landsat and the derivative grayscale images.

Sakaerat Biosphere Reserve as the study site

The site is located in Nakhorn Rachasima province of Thailand (Figure 2a). The Sakaerat Biosphere Reserve is located in the middle of the 225 km^2 area shown in Figure 2. Different vegetation types are randomly distributed in the biosphere reserve. Site details have been described elsewhere (DOI and SAKURAI, 2004; MURATA *et al.,* 2009; TRISURAT *et al.,* 2011; DOI and RANAMUKHAARACHCHI, 2013). The annual precipitation is 1,260 mm and the mean annual temperature is 26°C. The climate is classified as savanna (KÖPPEN, 1931). The natural vegetation type of the area is tropical dry evergreen forest dominated by *Hopea ferrea* and *Shorea* spp (KANZAKI *et al.,* 1995). Dry deciduous forest is another type of vegetation in the site (SAHUNALU *et al.,* 1995). The dry deciduous forest is more open compared to the evergreen forest. The dominant tree species are *Shorea obtusa, Pentamo suavis, Dipterocarpus intricatus, Gardenia* spp., and others. There are some grass species, such as *Arundinaria pusilla* and *Imperata cylindrica*. Human-induced fire burns these grass species in the dry season. Plantation plots were established in the late 1980s and are scattered throughout the area (Figure 2). Most of the plantation plots had previously been subjected to slash-and-burn shifting cultivation and then abandoned (MANINAN *et al.,* 1976). Some of the abandoned portions of Sakaerat had been converted into reforestation plantation plots. *Acacia mangium* and *Pterocarpus macrocarpus* were two of the introduced tree species. The secondary regeneration of various tree species comprises another type of vegetation in Sakaerat. In the secondary regeneration area (Figure 2), drought- and fire-tolerant tree species have been returning after intensive deforestation, including slash-and-burn shifting cultivation. These vegetation types are considered to form a forest conservation-degradation gradient (LAMOTTE *et al.*, 1998).

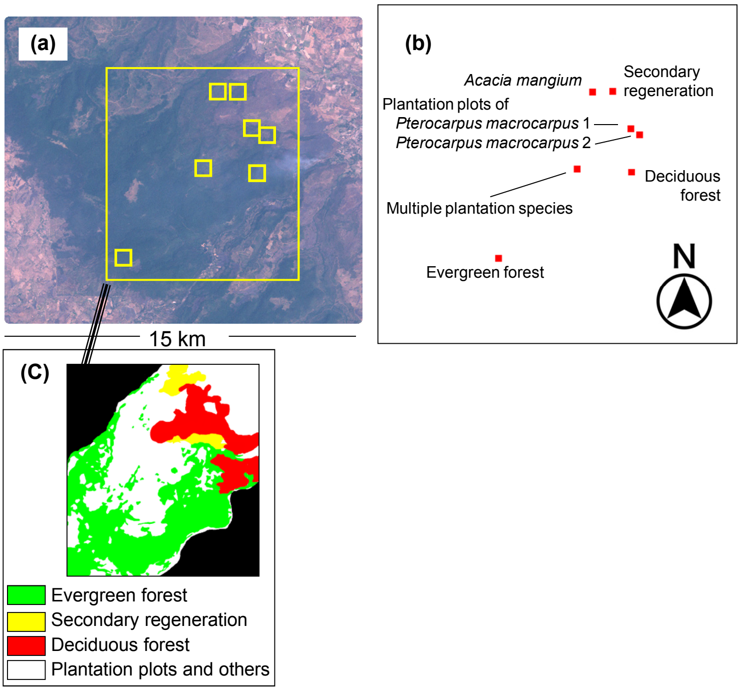

Figure 2 *- Red-green-blue true color image of the study site, Sakaerat in Nakhorn Rachasima province of Thailand (a), further analyzed areas of different vegetation types (b) and distribution of vegetation types described in Maninan et al. (1976) (c). To compare datasets on values of pixel grayscale intensity for the original 7 Landsat and all 22 grayscale images, the red squares (b) were used. Approximate locations of the squares (b) are shown in the original true color image (a)*

Image preparation

Satellite imagery data acquired by the Landsat 7 satellite on Nakhorn Rachasima province in Thailand (Figure 2a) were downloaded from the US Global Survey site (http://www.usgs.gov/). The Landsat data were acquired on 18 February 2002. The data were recorded as grayscale images for bands of blue (wavelength 441–514 nm, band 1), green (519–601 nm, band 2), red (631–692 nm, band 3), near-infrared (772–898 nm, band 4), mid-infrared 1 (1.55–1.75 μm, band 5), thermal infrared (10.3–12.4 μm, band 6), and mid-infrared 2 (2.06–2.35 μm, band 7) (KRAMER, 2012). A 15 km × 15 km area was selected in the original Landsat scene.

The original Landsat grayscale images for blue (band 1), green (band 2), and red (band 3) were used to prepare R-G-RGB yellow (RGrgbyB) and R-G-inverted RGB yellow (RGrgby^{-1}B) pseudo-color images (DOI, 2014). In this study, the Adobe RGB color space was chosen as one of the RGB color spaces. From the RGrgbyB and RGrgby^{-1}B JPEG images, the grayscale images that show the intensity values of cyan (C), magenta (M), yellow (Y), key black (K), and lightness (L^*) and the values of a^* and b^* were prepared. The International Commission on Illumination $L^*a^*b^*$ color model was designed to approximate human vision (KAKUMANU *et al.*, 2007). The three coordinates of $L^*a^*b^*$ represent the lightness of the color (L^*), its position between red/magenta and green (a^*), and its position between yellow and blue (b^*). Hereafter, the C, M, Y, K, L^*, a^*, b^*, and RGB yellow images are referred to as derivative grayscale images. CMYK images were generated with the International Color Consortium profile of US Web Coated (SWOP) v2 for digital output such as color printing. As an RGB yellow grayscale image (DOI, 2012) was also prepared, 15 grayscale images were added to the original 7 Landsat grayscale images. The sensor's original spatial resolution of 30 m × 30 m per pixel was retained.

Clustering of pixels

The set of 7 Landsat grayscale images or that of all 22 grayscale images was used in the clustering of the pixels in the image by running the pixel analysis software, MultiSpec 3.3 (Purdue Research Foundation). The iterative self-organizing data analysis (ISODATA) technique (BALL and HALL, 1968) was applied to cluster the pixels in the JPEG image. The minimum cluster size was 20 pixels. As the criteria for differences among pixels, the first critical distance was

25, 32, or 40 Euclidean distance and the other critical distances were 50, 64, or 80 Euclidean distances. These distances were selected because, with the 7 Landsat images, 7 to 18 clusters were generated in the entire image of the site where several major vegetation types were recognized.

Statistical analyses and image handling

Clusters generated by running Multispec were principal component-scored using the statistical software SPSS 10.0.1 (SPSS Inc.). For each cluster, the author used the mean values of the grayscale intensity for the seven Landsat grayscale images. The most significant principal component that indicates evergreen forest-likelihood was extracted. The clusters were scored on the principal component to represent evergreen forest-likelihood. The principal component scores for the clusters were converted to values between 0 (least likely) and 255 (most likely), which were indicated as complete black and white, respectively, in the grayscale image. Three grayscale images that resulted in the clustering at the pairs of critical distances were merged at the same weight (DOI, 2013) to obtain a grayscale map that indicates the evergreen forest-likelihood of the pixels in the image. In another layer overlapping the merged grayscale image, 10 pixel × 10 pixel grids were set on areas of *A. mangium* plantation, secondary generation in the northeastern part, *P. macrocarpus* plantation, multiple plantation tree species, fire-protected deciduous forest (SAKURAI *et al.*, 1998), and evergreen forest (Figure 2). Profiles of the 100 pixels were compared between the sets of the 7 Landsat images and all 22 grayscale images. Using the SPSS software, the Dunnett's T3 t-test was performed to evaluate significance of differences in evergreen forest-likelihood among means for the plots represented by the squares in Figure 2 a,b.

Results and discussion

A total of 100 clusters were generated with the six combinations (three pairs of critical distances × two sets of grayscale images, Table 1). Using all 22 grayscale images, a larger number of clusters was generated than by using the original Landsat images only. This demonstrates the enhanced power to discriminate among different pixels with the derivative grayscale images (ZAR, 1999). The current clustering algorithm discriminates among different pixels more accurately when the number of classes becomes larger (JIA and RICHARDS, 2002; MARTIN *et al.,* 2014). The enhanced discriminatory power was thought to have reduced the nuisance effects of the intra-variation of canopy/leaf reflectance within a single vegetation type or species that could blur spectral differences (MARTIN *et al.,* 2014).

Analyzing the multivariate profiles of the clusters based on the mean values of grayscale intensity showed that the derivative grayscale images added more information, which made the data structure richer than that for the original Landsat images only (Table 2) (De SENA *et al.*, 2000). When mean grayscale intensity values for the seven Landsat images were used for analyzing the mean grayscale intensity profiles of the 100 clusters, the statistical analysis extracted a single principal component with an eigenvalue of greater than 1, which is regarded to be sufficiently significant (Table 2) (KAISER, 1960). Eigenvectors for the seven bands were 0.875 (mid-infrared 1, Table 2) or greater, indicating that the first principal component was positively and linearly correlated with changes in pixel grayscale intensity in the seven Landsat images. In contrast, when the mean grayscale intensity profiles of the 63 clusters generated from the 22 grayscale images (Table 1) were used, two principal components with eigenvalues greater than 1 were obtained (Table 2). The first principal component was obviously quite similar to the one extracted from the Landsat images-only data according to the eigenvectors that exceeded 0.851. The first principal component explained 70% of the total variation whereas the second principal component explained 25%. This relationship between the principal components indicates the greater dimensionality revealed by the 22 grayscale intensity variables than the original Landsat variables that showed a much simpler data structure as represented by the single principal component that explained 92% of the total variation. The second principal component extracted from the dataset for 63 mean grayscale intensity profiles based on the 22 variables (Table 2) was largely contributed by some derivative variables, such as the value of a^* for the grayscale image from the RGrgbyB pseudo-color image when the variable did not significantly correlate with the first principal component. Thus, the second principal component was expected to help discriminate among pixel clusters with different profiles (DOI and SAKURAI, 2004; DE SENA *et al*., 2000).

According to Table 2, blue and other variables of grayscale intensity have positive correlations. This indicates that dark pixels in the grayscale images have small principal component 1 scores. In Sakaerat, the grayscale intensity values for bands 1 to 3 are smallest for the dark evergreen forest canopy (DOI and RANAMUKHAARACHCHI, 2010), largest for the most degraded bare ground, and in between for the *Acacia auriculiformis* plantation (DOI and RANAMUKHAARACHCHI, 2010, 2013). Tables 1 and 2 also show that the dark pixels tended to have small grayscale intensity values in the fifth Landsat grayscale image (band 5). This indicates that the dark pixels represent the moistest vegetation type. As water bodies are negligible in the site, the darkest and moistest clusters in Table 1 were most likely to represent the evergreen forest (DOI and SAKURAI, 2004). Therefore, clusters with principal component 1 scores of -0.5 or smaller were explored as those possibly representing the evergreen forest. Among principal component 1 scores for the clusters, the smallest value was -0.71 (Table 1). Hence, all pixels of the clusters with principal component 1 scores of -0.70 or smaller were converted to be completely white (grayscale intensity = 255) and shown as the most evergreen forest-likely in the clustering map. Likewise, pixels of clusters with principal component 1 scores of -0.50 or larger were colored with complete black (grayscale intensity = 0). Pixels of the other clusters with principal component scores between -0.50 and -0.70 were gray-scaled using the following equation.

$$\text{Grayscale intensity value of pixels in the cluster} = 255 \times (-0.50 - \text{Principal component 1 score for the cluster}) / [-0.50 - (-0.70)]$$

$$(-0.50 > \text{Principal component 1 score} > -0.70) \qquad (1)$$

All clusters were gray-scaled and mapped in Figure 3. The visual appearance of the maps is more consistent for the sets of the 22 grayscale images (Figure 3d-f), resulting in mean grayscale intensity values of 75 and 76. The maps generated from the seven Landsat grayscale images were less consistent (Figure 3a-c). The map from the seven Landsat images at 25 and 50 critical distances resulted in many dark pixels around the south-central part of the area (Figure 3a) that is covered by undisturbed evergreen forest (MANINAN, 1976; MURATA 2009, Figure 2). This map was thought to contain a large number of misclassified pixels and to thus be misleading. At 32 and 64 critical distances, the use of the 7 Landsat images resulted in a grayscale map (Figure 3b) that was similar to that from the 22 grayscale images (Figure 3d-f). However, at 40 and 80 critical distances, the evergreen forest-likelihood was abruptly visualized (Figure 3c), indicating a significant loss of information (Table 1).

Table 1 - Clusters with principal component 1 scores of -0.50 or smaller provided by principal component analysis of mean grayscale intensity profiles of all 100 clusters for the original 7 Landsat variables

Number of grayscale images used	Critical distances		Number of clusters generated	Evergreen forest-likelihood rank among clusters for the clustering condition (Principal component score < -0.51 only listed)	Mean grayscale intensity values for the Landsat grayscale variables (Band numbers)							Principal component 1 score	Evergreen forest likelihood Intensity in Figures. 3-5)	Number of pixels in the entire image (Figure 3)	Number of pixels with PC1 score < -0.51
	1	2			1	2	3	4	5	6	7				
7	25	50	18	1	71	51	41	55	50	128	128	-0.71	255	27,385	143,123
				2	71	52	42	67	58	129	129	-0.64	182	39,963	
				3	74	55	48	58	66	131	131	-0.59	111	30,922	
				4	72	54	44	74	69	129	129	-0.57	84	26,072	
				5	76	57	55	54	80	133	133	-0.50	4	18,781	
	32	64	12	1	72	51	42	56	52	129	129	-0.69	245	36,577	157,025
				2	72	53	43	67	60	129	129	-0.63	162	52,787	
				3	72	55	46	74	72	130	130	-0.54	50	25,235	
				4	75	56	52	57	76	132	132	-0.53	36	42,426	
	40	80	7	1	72	53	43	63	59	129	129	-0.64	178	108,055	169,561
				2	75	57	52	62	80	132	132	-0.50	1	61,506	
22	25	50	30	1	70	50	40	59	52	128	128	-0.70	255	35,531	132,091
				2	73	53	45	58	60	130	130	-0.63	162	27,634	
				3	71	53	42	72	64	129	129	-0.60	130	38,565	
				4	74	56	49	63	72	131	131	-0.55	58	30,361	
	32	64	20	1	71	51	40	59	52	128	128	-0.70	250	41,316	127,400
				2	72	53	42	71	64	129	129	-0.60	132	45,194	
				3	74	55	48	60	68	131	131	-0.58	100	40,890	
	40	80	13	1	71	51	41	63	55	128	128	-0.67	220	61,467	160,886
				2	73	54	46	65	66	130	130	-0.58	108	58,379	
				3	75	57	53	59	79	132	132	-0.51	8	41,040	

***Table 2** - Eigenvectors for grayscale intensity variables of profiles of the clusters generated by ISODATA clustering of the Sakaerat image with and without the derivative grayscale images. The eigenvectors were provided by principal component analysis of mean grayscale intensity profiles of all 100 for the original Landsat variables or of 63 clusters for the 22 variables*

Direct source of grayscale image(s)	Landsat band	Grayscale intensity variable	Sets of grayscale intensity variables used for principal component analysis (number of intensity variables and clusters)			
			Landsat variables only (Seven variables, 100 clusters)		Landsat and derivative grayscale variables (22 variables, 63 clusters)	
			PC 1§† (92%, Eigenv.‡ 6.5)	PC 2 (4%, Eigenv. 0.3)	PC 1 (70%, Eigenv. 15)	PC 2 (25%, Eigenv. 5.6)
Landsat grayscale images	1	Blue	0.989	-0.140	0.930	0.365
	2	Green	0.987	-0.109	0.959	0.274
	3	Red	0.966	0.066	0.998	0.029
	4	Near-infrared	0.956	-0.126	0.852	0.481
	5	Mid-infrared 1	0.875	0.474	0.858	-0.030
	6	Thermal infrared	0.980	-0.129	0.876	0.446
	7	Mid-infrared 2	0.964	0.015	0.900	0.257
Images for bands 2 and 3		RGB yellow			0.985	-0.157
RGrgbyB pseudo-color image		C			0.987	0.093
		M			0.908	0.389
		Y			0.832	-0.552
		K			0.708	-0.619
		*L**			0.989	0.135
		*a**			0.167	-0.970
		*b**			0.311	0.946
RGrgby^{-1}B pseudo-color image		C			0.977	-0.133
		M			0.983	0.034
		Y			-0.389	0.879
		K			-0.372	0.870
		*L**			0.957	0.279
		*a**			-0.878	0.372
		*b**			0.773	-0.614

§ Principal component

† Used for principal component 1 scoring and determination of evergreen forest-likelihood (Table1)

‡ Eigenvector

Figure 4 shows maps of integrative evergreen forest-likelihood of pixels prepared by merging the three grayscale maps (Figure 3) at the same weight to improve the reliability. The map from the seven Landsat images (Figure 4a) was darker than the other, and was obviously inhibited by the loss of information (Figure 3c, Table 1). However, the differences between the sets of grayscale images were less outstanding than in Figure 3. Therefore, merging the three grayscale maps in Figure 3 was demonstrated to improve the reliability of information revealed as the pixel intensity when the single grayscale maps showed wobble among the pairs of critical distances (Figure 3a-c) (DOI, 2013).

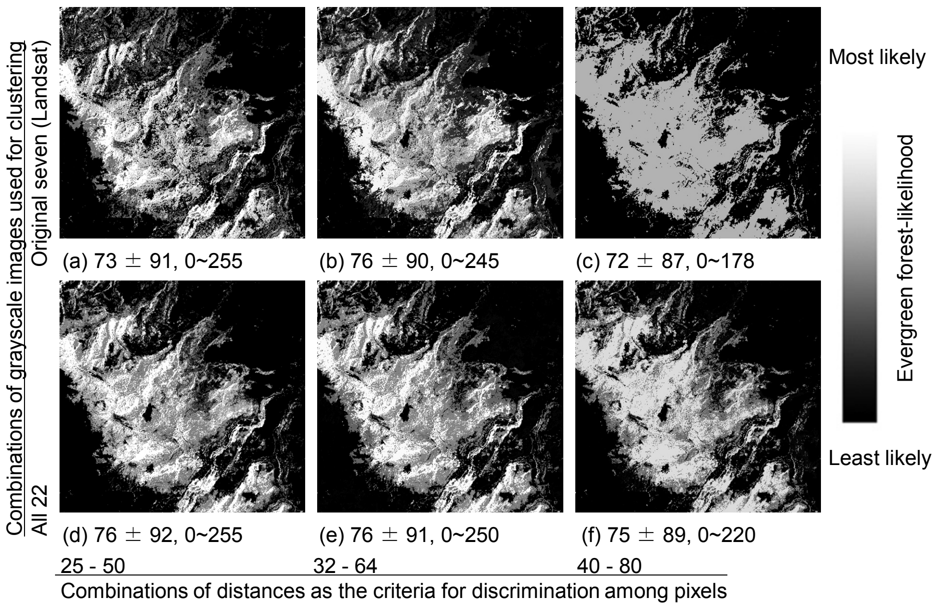

Figure 3 *- Maps of evergreen forest-likelihood of the pixels generated from different combinations of grayscale images and critical distances. Values indicate mean ± standard deviation and range of the grayscale intensity values for the pixels*

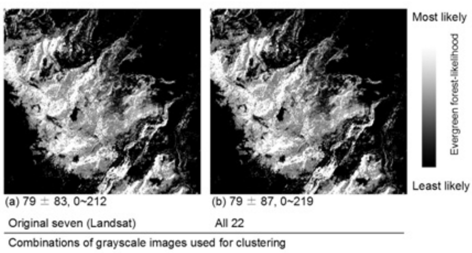

Figure 4 *- Maps of evergreen forest-likelihood of the pixels generated by overlapping the three grayscale images in Figure 3. The three grayscale images were merged at the same weight. Values indicate mean ± standard deviation and range of the grayscale intensity values for the pixels*

When pixel distribution patterns are observed in detail, however, differences between the grayscale image sets remain clear (Figure 5). For example, when only the seven Landsat images were used, by indicating brighter pixels, the ecological restoration effects of *A. mangium* and multiple tree species were evaluated as greater than in the other case with the 22 grayscale images. For the *A. mangium* plots, the values of evergreen forest-likelihood were 45 (±20, Landsat) and 18 (±29, all 22 images), which differed statistically ($p < 0.05$) and visually (Figure 5). Also, with the Landsat images only, as shown by closer mean grayscale intensity values, discriminating between the deciduous forest and the evergreen forest was less successful than with the 22 grayscale images. Pixels for the deciduous forest generated from the 22 grayscale images were darker than those in the counterpart image. These differences between the sets of grayscale images suggested the enhancement of discrimination among vegetation types by the derivative grayscale images.

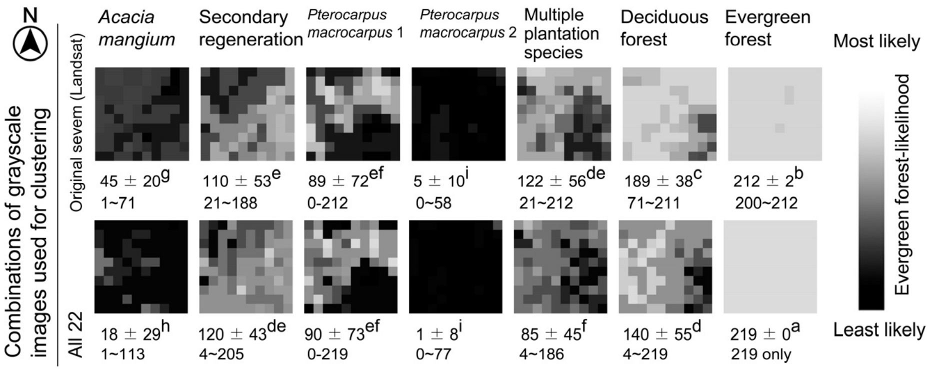

Figure 5 *- Detail 300 m × 300 m maps of evergreen forest-likelihood of the pixels in the red squares of vegetation types in Figure 1b. Values indicate mean ± standard deviation and range of the grayscale intensity values for the pixels in the square of 100 × 100 pixels. Means followed by the same superscript letter do not differ significantly at p = 0.05 according to the Dunnett's T3 t-test*

As shown in the evergreen forest-likelihood distribution patterns in the plots (Figure 5), results may vary significantly depending on the sets of grayscale images (CONGALTON *et al.*, 2014). In previous studies, rubber plantations and natural tropical forests were successfully discriminated between (DONG *et al.*, 2013; SENF *et al.*, 2013), likely due to the simple species composition of the plantations. However, it is more difficult to precisely cluster pixels that represent multiple vegetation types when each of the vegetation types includes canopies of multiple tree species. As previously described by HAYES and SADER (2001), the increase in non-linearity among the grayscale variables is important (Table 2, Figure 1b). MARIOTTO *et al.* (2013) showed the effects of non-linearly converted Landsat 7 variables in discriminating between cotton and other crops in central Asia. In this study, similar non-linear effects of the pseudo-color imaging method were shown to aid in discrimination among vegetation types (Table 1).

Figure 6 shows the enhancement of statistical discrimination among plots of different vegetation types. According to the Dunnett's T3 *t*-test, relying on the Landsat images only, the secondary regeneration plot could not be discriminated from the multiple plantation species and *P. macrocarpus* 1 plots (Figure 6a). This difficulty was, however, overcome by using all 22 grayscale images (Figure 6b). The secondary regeneration plot was discriminated from the multiple plantation species and *P. macrocarpus* 1 plots. Thus, through the addition of the derivative grayscale images, pixels in the seven plots were successfully *t*-test-discriminated (Figure 6). The significance in the difference between the evergreen forest and deciduous forest plots increased from $p = 5.44 \times 10^{-7}$ to $p < 10^{-14}$. Before the Landsat 7 image acquisition in 2002, the deciduous forest had been fire-protected for 35 years (SAKURAI *et al.*, 1998). The top soil was comparable to that of the evergreen forest in terms of various soil properties. However, the deeper soil layers below 10 cm depth are much poorer than those of the evergreen forest soil (SAKURAI *et al.*, 1998). Hence, the deciduous forest was very likely still recovering the original characteristics of the evergreen forest. The pseudo-color imaging method improves discrimination among objects by enriching the original information on the intensity values of red, green, and blue. The Landsat images contained information on RGB-based color, moisture, and thermal radiation. In addition to the informative physical measures of moisture and temperature, the derivative grayscale images derived from the RGB grayscale images aided in the discrimination among the vegetation types. This was also the case in a previous study in which derivative grayscale images generated from an RGB image significantly improved the discrimination between rice and soybean canopies, both of which were comparably dark green (DOI, 2016). As shown in the above comparison between evergreen and deciduous forests, ecological restoration can be differently quantified depending on observed aspects.

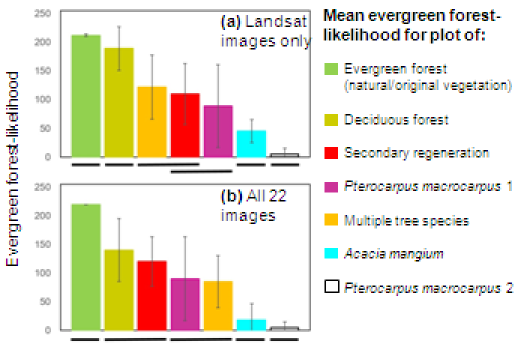

Figure 6 *- Evergreen forest-likelihood for pixels in the plots of different vegetation types in Sakaerat (Figure 2) based on original 7 Landsat images only (a) or all 22 grayscale images (b). The error bars indicate standard deviations. In each diagram of set of grayscale images (a or b), means on the same bold horizontal bar (——) do not differ significantly at p = 0.05 according to the Dunnett's T3 t-test*

With all 22 grayscale images, the secondary regeneration plot was evaluated to be recovering more than the multiple reforestation species and *P. macrocarpus* plots (Figures 5, 6b). TRISURAT (2010) recognized the secondary regeneration as a deciduous forest undergoing ecological restoration. DOI *et al.* (2010) observed that the secondary regeneration looked like a deciduous forest, and the soil showed intermediate profiles between those of the evergreen forest and bare ground (the most degraded vegetation type, DOI *et al.* 2009). The intermediate profile was, however, thought to be stagnant (TRISURAT, 2011) due to the running fire that hampers further ecological restoration. In Sakaerat, however, the running fire that occurs in the dry season (approximately December to April) may less seriously delay ecological restoration than in the monoculture reforestation of some single tree species such as *A. mangium* (Figures 5, 6). *A. mangium* is known for its alleloopathic effects on some tree species, including *Shorea* species which are biologically close to the *Shorea* species of Sakaerat (ANWAR, 1992). The litter is difficult to decompose due to its high lignin content (BINI *et al.*, 2013), and accumulates significantly, allowing few other plant species to come in (KRISNAWATI *et al.*, 2011). Although it is one of the fastest growing tree species among those used for reforestation, the aforementioned side effects could result in the *A. mangium* plot being quite different from the evergreen forest. For *P. macrocarpus,* allelopathy has not been reported, while this species is likely to be easily outcompeted by shade-tolerant tree species during the ecological restoration in the region (MAROD *et al.*, 2012). The western part of the *P. macrocarpus* 1 plot is adjacent to the evergreen forest (Figure 2). This likely facilitates the transfer of native tree species to the *P. macrocarpus* 1 plot, thus accelerating the ecological restoration (Figures 5,6). In contrast, the *P. macrocarpus* 2 plot is surrounded by other *P. macrocarpus* plots. This separated location, away from other vegetation types, was thought to be a significant cause of the delay (Figures 5 and 6) in the restoration of the original ecosystem revealed as an evergreen forest-like canopy.

Conclusions

Using Landsat 7 grayscale images of the Sakaerat Biosphere Reserve, information carried by the original seven images was enriched by the pseudo--color imaging method. This enrichment was recognized as increases in data structural dimensionality and in the number of clusters generated by ISODATA computation. By using separate sets of the 7 Landsat images and all 22 grayscale images to score the pixels of the Sakaerat image on the basis of tropical dry evergreen forest-likelihood, plots of seven vegetation types that differed in the intensity of deforestation or the degree of ecological restoration were statistically discriminated; the use of each image set alone did not enable complete discrimination of plots. Using the pseudo-color imaging method and observing a plantation plot of *A. mangium* and a *P. macrocarpus* plot located in the center of a large *P. macrocarpus* plantation area, the plots were found to have achieved significantly less ecological restoration than the secondary regeneration dominated by drought- and fire-tolerant trees that were subjected to running fire in the dry season. The combining of this imaging method with devices that enable the real-time observation of vegetation is rapidly becoming more feasible as a result of current advancements in multispectral sensors and related devices. To realize advances in management, the pseudo-color imaging and derivative grayscale images are worth being examined and developed in order to observe forests and other vegetation types.

References

ANWAR, C., 1992. The growth of *Shorea* seedlings on soil media of several age levels of *Acacia mangium* stands. *Bul. Pen. Hutan* **544**: 9-16.

BALL, G.H., HALL, D.J., 1968. *ISODATA: a method of data analysis and pattern classification.* Stanford Research Institute, Office of Naval Research Information Sciences Branch Menlo Park, United States, 61 pp.

BINI, D., FIGUEIREDO, A.F., DA SILVA, M.C.P., VASCONCELLOS, R.L. DE F., CARDOSO, E.J.B.N., 2013. Microbial biomass and activity in litter during the initial development of pure and mixed plantations of *Eucalyptus grandis* and *Acacia mangium*. *R Bras Ci Solo* **37**: 76-85.

CHAVES, A., LA SCALEA, R., COLTURATO, A., KAWABATA, C., FURTADO, E., BRANCO, K., 2015. Using UAVs and digital image processing to quantify areas of soil and vegetation. *Journal of Physics: Conference Series*. pp. 12112-12115.

CONGALTON, R.G., GU, J., YADAV, K., THENKABAIL, P., OZDOGAN, M., 2014. Global land cover mapping: a review and uncertainty analysis. *Remote Sens* **6**: 12070-12093.

DE SENA, M.M., POPPI, R.J., FRIGHETTO, R.T.S., VALARINI, P.J., 2000. Evaluation of the use of chemometric methods in soil analysis. *Quim Nova* **23**: 547-556.

DEERY, D., JIMENEZ-BERNI, J., JONES, H., SIRAULT, X., FURBANK, R., 2014. Proximal remote sensing buggies and potential applications for field-based phenotyping. *Agronomy* **4**: 349-379.

DOI, R., 2012. Simple luminosity normalization of greenness, yellowness and redness/greenness for comparison of leaf spectral profiles in multi-temporally acquired remote sensing images. *J Biosci* **37**: 723-730.

DOI, R., 2013. Discriminating crop and other canopies by overlapping binary image layers. *Opt Eng* **52**: Article number 020502.

DOI, R., 2014. Red-and-green-based pseudo-RGB color models for the comparison of digital images acquired under different brightness levels. *J Modern Opt* **61**: 1373-1380.

DOI, R., 2016. Improved discrimination among similar agricultural plots using red-and-green-based pseudo-colour imaging. *Int Agrophys* **30**: 151-163.

DOI, R., ARIF, C., SETIAWAN, B.I., MIZOGUCHI, M., 2014. Pixel color clustering of multi-temporally acquired digital photographs of a rice canopy by luminosity-normalization and pseudo-red-green-blue color imaging. *Sci World J* **2014**: Article number 450374.

DOI, R., RANAMUKHAARACHCHI, S.L., 2010. Discriminating between canopies of natural forest and *Acacia* plantation plots in a Google Earth Image to evaluate forest land rehabilitation by *Acacia* species. *Int J Agric Biol* **12**: 921-925.

DOI, R., RANAMUKHAARACHCHI, S.L., 2013. Slow restoration of soil microbial functions in an Acacia plantation established on degraded land in Thailand. *Int J Environ Sci Technol* **10**: 623-634.

DOI, R., SAHUNALU, P., WACHRINRAT, C., TEEJUNTUK, S., SAKURAI, K., 2009. Antibiotic resistance profiles of soil bacterial communities over a land degradation gradient. *Community Ecol.* **10**: 173-181.

DOI, R., SAKURAI, K., 2004. Principal components derived from soil physicochemical data explained a land degradation gradient, and suggested the applicability of new indexes for estimation of soil productivity in the Sakaerat Environmental Research Station, Thailand. *Int J Sust Dev World Ecol* **11**: 298-311.

DOI, R., WACHRINRAT, C., TEEJUNTUK, S., SAKURAI, K., SAHUNALU, P., 2010. Semiquantitative color profiling of soils over a land degradation gradient in Sakaerat, Thailand. *Environ Monit Assess* **170**: 301-309.

DONG, J., XIAO, X., CHEN, B., TORBICK, N., JIN, C., ZHANG, G., BIRADAR, C., 2013. Mapping deciduous rubber plantations through integration of PALSAR and multi-temporal Landsat imagery. *Remote Sens Environ* **134**: 392-402.

EHSANI R., SANKARAN S., MAJA J., NETO J.C., 2012. Affordable multi-rotor remote sensing platform for applications in precision horticulture. Proceedings of the *12th International Conference on Precision Agriculture*. July 15-18, 2012, Indianapolis, Indiana.

HAYES, D., SADER, S., 2001. Comparison of change-detection techniques for monitoring tropical forest clearing and vegetation regrowth in a time series. *Photogramm Eng Remote Sensing* **67**: 1067-1075.

JIA, X., RICHARDS, J., 2002. Cluster-space representation for hyperspectral data classification. *Geoscience and Remote Sensing, IEEE Transactions on* **40**: 593-598.

KAISER, H.F., 1960. The application of electronic computers to factor analysis. *Educ Psychol Meas* **20:** 141-151.

KAKUMANU, P., MAKROGIANNIS, S., BOURBAKIS, N., 2007. A survey of skin-color modeling and detection methods. *Pattern Recogn* **40**: 1106–1122.

KANZAKI, M., YODA, K., DHANMANONDA, K., 1995. Mosaic structure and tree growth pattern in a monodomoinant tropical seasonal evergreen forest in Thailand. In: Box, E.O., Peet, R.K., Masuzawa, T., Yamada, I., Fujiwara, K., Maycosk, P.F. (Eds.), Vegetation science in forestry. Kluwer Publishers, Netherlands, pp. 495-513.

KÖPPEN, W., 1931. *Grundriss der Klimakunde.* Walter de Gruyter, Berlin, Germany, 388 pp.

KRAMER H.J., 2012. *Observation of the Earth and its Environment: Survey of Missions and Sensors*. Springer Science & Business Media. Heidelberg, Germany, 1510 pp.

KRISNAWATI, H., KALLIO, M., KANNINEN, M., 2011. *Acacia mangium Willd.: ecology, silviculture and productivity*. Center for International Forestry Research, Bogor, Indonesia, 15 pp.

LAMOTTE, S., GAJASENI, J., MALAISSE, F., 1998. Structure diversity in three forest types of north-eastern Thailand (Sakaerat Reserve, Pak Tong Chai) *BASE: Biotechnologie, Agronomie, Societe et Environnement* **2**: 192-202.

MANINAN, C., KAEONIAM, P., KHOORAT, P., SUNTHORNSAN, W., ISSAREEYA, M., CHERDCHUN, C., BUACHUM, W., 1976. *A study of illegal deforestation in the reserved forest area at the Sakaerat Environmental Research Station.* Environmental and Ecological Research Department, Applied Scientific Research Corporation of Thailand, Bangkok. 76 pp.

MARIOTTO, I., THENKABAIL, P.S., HUETE, A., SLONECKER, E.T., PLATONOV, A., 2013. Hyperspectral versus multispectral crop-productivity modeling and type discrimination for the HyspIRI mission. *Remote Sens Environ* **139**: 291-305.

MAROD, D., DUENGKAE, P., KUTINTARA, U., SUNGKAEW, S., WACHRINRAT, C., ASANOK, L., KLOMWATTANAKUL, N., 2012. The influences of an invasive plant species (*Leucaena leucocephala*) on tree regeneration in Khao Phuluang Forest, Northeastern Thailand *Kasetsart J (Nat Sci)* **46**: 39-50.

MARTIN, R., BRABYN, L., BEARD, C., 2014. Effects of class granularity and cofactors on the performance of unsupervised classification of wetlands using multi-spectral aerial photography. *J Spat Sci* **59**: 269-282.

MULLA, D.J., 2013. Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosyst Eng* **114**: 358-371.

MURATA, N., OHTA, S., ISHIDA, A., KANZAKI, M., WACHIRINRAT, C., ARTCHAWAKOM, T., SASE, H., 2009. Comparison of soil depths between evergreen and deciduous forests as a determinant of their distribution, Northeast Thailand. *J For Res* **14**: 212-220.

NEBIKER, S., ANNEN, A., SCHERRER, M., OESCH, D., 2008. A light-weight multispectral sensor for micro UAV—Opportunities for very high resolution airborne remote sensing. *Int Arch Photogram Rem Sens Spatial Inform Sci* **37**: 1193-1200.

OLSZEWSKA, M., GRZEGORCZYK, S., ALBERSKI, J., BALUCH-MALECKA, A., KOZIKOWSKI, A., 2008. Effect of copper deficiency on gas exchange parameters, leaf greenness (SPAD) and yield of perennial ryegrass (*Lolium perenne* L.) and orchard grass (*Dactylis glomerata* L.). *J Elementol* **13**: 597-604.

SAHUNALU, P., DHANMANONDA, P., 1995. Structure and dynamics of dry dipterocarp forest, Sakaerat, northeastern Thailand. In: Box, E.O., Peet, R.K., Masuzawa, T., Yamada, I., Fujiwara, K., Maycosk, P.F. (Eds.), Vegetation science in forestry. Kluwer Publishers, Netherlands, pp. 465-494.

SAKURAI, K., TANAKA, S., ISHIDUKA, S., KANZAKI, M., 1998. Differences in soil properties of dry evergreen and dry deciduous forests in the Sakaerat Environmental Research Station. *Tropics* **8**: 61-80.

SENF, C., PFLUGMACHER, D., VAN DER LINDEN, S., HOSTERT, P., 2013. Mapping rubber plantations and natural forests in Xishuangbanna (Southwest China) using multi-spectral phenological metrics from MODIS time series. *Remote Sens* **5**: 2795-2812.

SICHER, R.C., 1999. Photosystem-II activity is decreased by yellowing of barley primary leaves during growth in elevated carbon dioxide. *Int J Plant Sci* **160**: 849-854.

TONG, Q., XUE, Y., ZHANG, L., 2014. Progress in hyperspectral remote sensing science and technology in China over the past three decades. *Selected Topics in Applied Earth Observations and Remote Sensing, IEEE Journal of* **7**: 70-91.

TRISURAT, Y., 2010. Land use and forested landscape changes at Sakaerat Environmental Research Station in Nakhorn Ratchasima province, Thailand. *Ekológia* **29**: 99-109.

TRISURAT, Y., DUENGKAE, P., 2011. Consequences of land use change on bird distribution at Sakaerat Environmental Research Station. *J Ecol Field Biol* **34**: 203-214.

ZAR, J.H., 1999. *Biostatistical analysis*. Fourth edition, Prentice Hall, New Jersey, 663 pp.

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Mixed Forests Research in Portugal

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Abstract. Mixed-species forests are complex systems in which individual trees of different species interact with each other and with the environment. There are sound ecological and cultural arguments supporting the interest in mixed-species stands silviculture and its potential increase in productivity *vs.* single-species. To understand such complex systems is necessary to incorporate interspecific competition effects, in order to predict stand dynamics under different environments and/or management regimes. Mixed-species forests have become, due to their advantages, an important centre of attention in forest research. Because the size of mixed plantations has increased in the last decades it is now a matter of particular relevance to forestry the evaluation of their performance and productivity, especially in the conifer-broadleaves mixtures. The aim of this study was to, taking into consideration its characteristics, structure and dynamics, review mixed-species forests. A compilation of the research on mixed forests conducted in Portugal is also presented, according to the main types of mixed-species stands: existing mixed-species stands, conversion of pure stands into mixed stands, mixed-species plantations and mixed-species experimental trials.
Key words: Mixed-species stands, growth, management, forest structures, competition, review

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Investigação em florestas mistas em Portugal
Sumário. Florestas mistas são sistemas complexos em que árvores de diferentes espécies interagem entre si e com o ambiente que as rodeia. Existem argumentos sólidos, culturais e ecológicos, que suportam o interesse da silvicultura de povoamentos mistos e da sua potencial capacidade produtiva comparada com povoamentos puros. Estas vantagens levaram a que as florestas mistas tornaram-se gradualmente o foco da investigação florestal. Compreender estes sistemas complexos, incorporando efeitos de competição interespecífica, é necessário para auxiliar na predição das dinâmicas de crescimento existentes nos povoamentos, em diversos ambientes e/ou formas de gestão. A necessidade de compreender o crescimento e produtividade é, hoje em dia, uma questão de particular relevância para a gestão florestal dado que as plantações mistas têm aumentado em área nas últimas décadas devido aos potenciais benefícios económicos, especialmente em misturas de coníferas e folhosas. O objetivo deste estudo foi efetuar uma revisão bibliográfica das florestas mistas, tendo em consideração as suas características, estrutura e dinâmicas neste tipo de florestas. Além disso, uma compilação das investigações realizadas em Portugal em florestas mistas é apresentada de acordo com os principais tipos de povoamentos de espécies mistas: povoamentos de espécies mistas já existentes, conversão de povoamentos puros em povoamentos mistos, plantações de povoamentos mistos e ensaios experimentais de plantações mistas.
Palavras-chave: Povoamentos mistos, crescimento, gestão, estrutura, competição, revisão

Recherche sur les forêts mixtes au Portugal
Résumé. Les forêts mixtes sont des systèmes complexes dans lesquels les arbres de différentes espèces interagissent les uns avec les autres et avec leur environnement. Il existe des arguments solides, culturels et écologiques qui soutiennent les intérêts de la sylviculture de peuplements mélangés et sa capacité de production potentielle par rapport aux peuplements purs. Ces avantages ont fait progressivement des forêts mixtes l'objet de la recherche forestière. Comprendre ces systèmes complexes, intégrant les effets de la compétition interspécifique, aide à prédire la dynamique de la croissance des peuplements, dans des environnements différents et/ou sous gestions forestières différentes. Le besoin de comprendre la croissance et la productivité est, de nos jours, une question considérable pour la gestion forestière puisque la surface de plantations mixtes a accru au cours des dernières décennies, en raison des éventuels avantages économiques, particulièrement dans les mixtes de conifères et de feuillus. Cette étude a pour objectif une revue de littérature sur les forêts mixtes en tenant compte de ses caractéristiques, structure et dynamiques. En outre, un recueil des recherches faites au Portugal sur les forêts mixtes est exposé selon les principaux types de peuplements concernés: peuplements mélangés existants, conversion de peuplements purs en peuplements mélangés, plantations de peuplements mélangés et d'essais expérimentaux.
Mots-clés: Peuplements mélangés, croissance, gestion, structure, compétition, revue de littérature

Mixed-species forest

Description and development

All over the world many forest stands are composed by more than one species and Europe is no exception (BARTELINK and OLSTHOORN, 1999). Most natural forests consist in a mixture of two or more tree species (BURKHART and THAM, 1992; RACKHAM, 1992; SMITH, 1992). As a consequence of increasing concern for forest ecosystems and their sustainable management, forestry objectives are evolving at a rapid rate (SKOVSGAARD and EMBORG, 1999). The challenge now is to create and maintain forest types that favour both production and environmental targets. This has led to a renewed interest in the establishment and management of mixed-species forests (SKOVSGAARD and EMBORG, 1999; CHEN and POPADIEUK, 2002; JOHANSSON, 2003; SCHERER-LORENZEN *et al.*, 2005).

The importance of mixed-species stands has been recognized in Europe (ASSMANN, 1970) and a transformation of pure, even-aged stands, into mixed ones, and preferably uneven-aged forest stands, have been occurring (KENK, 1992; SKOVSGAARD and EMBORG, 1999; JOHANSSON, 2003). OLSTHOORN *et al.* (1999) stated that the area of mixed forest stands in Western Europe had increased. In fact, the area of forest occupied by mixed-species stands in Europe is still increasing today and represented in 2007 more than 70% of total forested area (MCPFE *et al.*, 2007). For example, the National Forest Inventory in German indicated that approx. 73% of German forests consist of mixed stands (BMELV, 2011). These changing forest structures and compositions stress, again, the need for tools to support decision making in mixed stands management. The trend in Europe for more diversified structures and a multi resource forest management has lead to a gradual change of pure pine stands into mixed structures, with hardwoods, and to the establishment of more mixed plantations areas (MASON and ALÍA, 2000; KINT *et al.*, 2006; FOREST EUROPE, UNECE and FAO, 2011).

According to the definition by the EU Concerted Action 'Management of Mixed-species Forest: Silviculture and Economics' AIR3-CT94-2149 (OLSTHOORN and HEKHUIS, 1995), a mixed-species forest comprises ‘stands composed of different tree species, mixed on a small scale, leading to competition between trees of different species as a main factor influencing growth and management'. But the definition used to identify a mixed forest stand is not universal among European countries (BARTERLINK and OLSTHOORN, 1999) and, as a consequence, the area under mixed-species stands definition can vary significantly. In most countries for a stand to be defined as mixed it must contain a minimum percentage of tree species other than the main tree species. In some cases the threshold is over 30% (JOHANSSON, 2003), which means that stands with relatively low proportions of other species are ignored. If this threshold was lowered, the actual area of mixed forest would be substantially larger than the official data and if the definition proposed by the EU Concerted Action were to be applied the estimates of the European mixed forest area would have to be revised dramatically upwards.

Only a limited effort to quantify growth and yield relationships in mixed-species stands has been made compared to the effort devoted to study pure and even-aged stands that have been extensively and successfully modelled for decades (e.g. BURKHART and THAM, 1992; KELTY, 1992; BARTELINK, 2000; GOBAKKEN and NÆSSET, 2002). This is largely explained by the historical role that forests have played, and still play, in human society (BARTELINK, 1999); the emphasis has been almost exclusively on single-species stands and many empirical stand-level growth models were developed and successfully used for plantation management (BARTELINK, 1999). Already in 1992 BURKHART and THAM had stated that models of growth and yield for mixed-species stands were required and essential to support management decisions. Stand composition plays a significant role in the function and structure of forest ecosystems. Models for mixed species are becoming more important due to the variety of possible species mixtures coupled with the varied range of environmental conditions under which the mixtures might grow.

The studies that have been implemented till now have shown that in some circumstances, like with species already adapted to site conditions, mixtures have advantages over single-species (KELTY, 1992, 2006). More than one species significantly influence the ecology of the stand by themselves and, principally, in combination. These stands generally have a very complex structure, incorporating interspecific competition effects. Some of the advantages that have been identified are: protection from disease and insect outbreak (SU *et al.*, 1996), resistance to wind damage and other abiotic stress (CUMMING, 2001), risk reduction (KENK, 1992), compensatory growth due to the increase nutrition (KELTY, 1992; BINKLEY, 2003), conservation of native plant and animal species, increased ecological diversity, and a more diverse habitat (CHEN and POPADIEUK, 2002). Other benefit improvements have been reported in nutrient cycling (FORRESTER *et al.*, 2006b), foliar nutrients (BROWN, 1992; RICHARDS *et al.*, 2010; NUNES *et al.*, 2011), soil fertility (MALCOLM and MASON, 1999; MONTAGNINI, 2000) and biomass production (BINKLEY and RYAN, 1998;

BINKLEY *et al.*, 2003; FORRESTER *et al.*, 2004). Mixed stands serve economical, ecological, and visual objectives by maintaining landscape aesthetics (KENK, 1992) and more closely approximate natural forests than single-species stands (LUCAS, 1991; RACKAM, 1992). Mixed stands, in an economic perspective, may also imply a spread of financial risks, as fluctuations of the wood market can be accommodated much more easily than with only one species (LU and BUONGIORNO, 1993). Mixed stands also provide a diverse range of products and a more varied ecosystem to encourage a wider range of animal species (BALL *et al.*, 1995; KEENAN *et al.*, 1995). Last but not least, mixed stands are widely recognized as sink sources to sequester carbon (KAYE *et al.*, 2000; RESH *et al.*, 2002; FORRESTER *et al.*, 2006a) and play an important role in the green house gas mitigation processes.

But mixed-species stands also present some disadvantages when compared with monocultures. The monoculture has the ability to concentrate all site resources in the growth of a single-species; there is simplicity in stand management and easy, standardized silviculture and harvest operations can be implemented. One of the main disadvantages of mixed stands is the harvest complexity. Their management is difficult because each species has a different growth habit (SMITH, 1986) and this characteristic makes it difficult to predict their development (LAVIGNE, 1992). The management of mixed stands requires more skills and additional understanding about the growth patterns and interactions between the mixed-species and, when needed, knowledge to convert mixed stands of undesirable composition into stands with the desired species composition. The efficient management of mixed stands can increase the profits for the owner as well as the wood quality (FRIVOLD and GROVEN, 1996).

In addition to studies on mixed-species resulting from natural regeneration, the major part of established mixed stands, with all the irregularities and complexities of natural woods, many studies have been done in mixtures of species in the simplified ecosystem of a plantation (CARVALHO OLIVEIRA, 1984; FRIEDRICH and DAWSON, 1984; BURESTI and FRATTEGIANI, 1994; KARMER, 1994; MALCOLM and MASON, 1999). Plantations are man created forests, by planting seeds or seedlings (WEST, 2006). Very often one of the species is planted and the other species is established by natural seedling or vegetative regeneration by sprouts, suckers or, sometimes, two species are planted together in a consociation (JOHANSSON, 2003). Species consociation in a mixed plantation can vary from tree by tree, or 'intimate mixture' (BOUDRU, 1986), alternative lines mixture, to strips or groups mixture. The selection of which species consociation to use on plantations depends upon the ecologic and/or economic objectives and the available silvicultural skills (MONTEIRO *et al.*, 1994). This type of mixed forest is expensive and demands great effort and good knowledge of species, planting techniques and plant development (JOHANSSON, 2003). The most successful plantations are stratified mixtures composed of faster-growing intolerant species above slower-starting tolerant ones (SMITH, 1986). If the trees in the upper canopy are not too dense and numerous, they grow more rapidly in stem diameter than they would if crowded into the single canopy of a pure plantation. The lower-stratum species can influence the stem form and help the self pruning of the upper-stratum species, just like it happens in a pure stand.

There are two basic experimental designs for testing the yield of mixtures under a range of species compositions or densities. In a replacement series, also called substitutive design, the species are substituted for one another in different proportions with total plant density held constant. In additive series, however, each species with a fixed density in monoculture is added in the mixture so that mixtures have greater total density than monoculture of each species (HARPER, 1977; VANDERMEER, 1989).

Permanent plots are an important tool for forest ecosystem research and can furnish crucial information to better understand the rates of forest production, nutrient cycling and tree mortality. They are useful for applied forest research and can also be used to provide long-term continuity to forest ecological studies.

Structure and dynamics analysis

Countries generally have multiple goals for their forest ecosystems (FAO, 1988). A greater diversity is often mentioned as a goal in the national policy plans. The greater variety in forest structure that results from natural processes is therefore highly appreciated and forest managers are encouraged to work with, rather than against, natural developments (BARTELINK and OLSTHOORN, 1999).

The concept of a potential increase in mixed-species stands production is of the most importance, but is not generally included into forestry practice (KELTY, 1992; MONTEIRO *et al.*, 1994). Ecological theory suggests that, under some conditions, forest stands which contain more than one tree species should potentially have a productivity advantage over monocultures. Such advantage is based in the assumption, by the fundamental niche separation theory, that two or more species must use resources differently if they are to coexist on a stand ecosystem (VANDERMEER, 1989). This difference in resources use among species suggests that the species in a mixture may utilize the resources of a site more completely than any single-species would be able to do. However, KELTY (1992) underlined the need to know, when mixed-species stands have greater total stand yields than monocultures, what were the conditions, or with what sets of species that was likely to occur.

OLIVER and LARSON (1990) reported examples of mixed-species consociation, like *Picea sitchensis* x *Alnus rubra*, *Picea sitchensis* x *Tsuga heterophylla*, *Abies amabilis* x *Tsuga heterophylla*. The effects of combining two species in a replacement series can be also analysed by comparing the yield of each species in mixture with its yield in monoculture (HARPER, 1977). This has commonly been used in yield studies where the proportion of both species is of interest. For any particular species mixture, a relative proportion and a total relative proportion can be calculated. Assuming the two species use resources in identical ways, the expected value of the first entity depends on the particular species proportion and the second one always equals 1.0 (KELTY, 1992). For any mixture a total relative proportion value greater than 1.0 indicates that either significant niche separation or a direct beneficial relationship among the species and suggests that a potential productivity advantage may exist in mixtures compared to monocultures; on the other hand values lower than 1.0 indicate the presence of an antagonistic relationship between the consociated species, some inhibition of the availability of resources may be occurring with overall growth reduction (BROWN, 1992; KELTY, 1992).

A number of studies have been done to compare yield in mixed-species with monocultures of the component species (ASSMANN, 1970; WIERMAN and OLIVER, 1979; KELTY, 1989; DEBELL *et al.*, 1997; FRIVOLD and KOLSTRÖM, 1999; MALCOLM and MASON, 1999; MACPHERSON *et al.*, 2001; CHEN and KLINKA, 2003; NUNES *et al.*, 2014). del RÍO *et al.* (2016) compiled a set of measures, indices and methods to characterize mixed stands forests in terms of structure, dynamics and productivity. In some circumstances, certain tree species will have higher yield in mixed plantations probably because they use resources differently if they coexist on a site and, in combination, are able to use more of the available resources. Potential reasons include, for instance, a change in canopy structure and light interception (NOBEL *et al.*, 1993), the decreased competition in crown and root, increased litter decomposition rates and enhanced mineralization rates. In addition, BROWN (1992) also indicated that mixtures of two or more species could be more or less productive than monocultures of the component species, depending on their interaction behaviour patterns.

Trees, in mixed stands, share resources of light, water and necessary nutrients for their survival and growth. Because resources are limited, there is interference between neighbouring trees of the same and different species. The mixed-species effect can be defined as the effect on productivity of the interspecific interaction between trees in a stand (GOBAKKEN and NÆSSET, 2002).

It is important to consider the direct effect of competition with neighbouring trees. However the verification of the mixed-species effect is not easy due to the difficulty in obtaining the comparative yields of the monocultures of the species of interest without being confounded by other factors (GOBAKKEN and NÆSSET, 2002). For instance, there is another effect that plays in interspecific competition: the spatial pattern, i.e. the effect of one tree on another determined by the distance between them (del RÍO *et al*., 2016). A high density of one species means that all trees are affected by this species and a reduction on stand density could maintain the general relationship. To reduce the competition is important to do a spatial arrangement of trees of different species.

KELTY (1992, 1994) signalled two different types of interactions between species that might cause yields in mixtures to exceed those in monocultures of the component species. This statement was based on VANDERMEER (1989) experiments with herbaceous species. These interactions are: complementarity, in which species differences in height, crown form, rooting depth, and/or phenology have reduced competition between them and make a more complete use of the site resources; and facilitation, in which the presence of one species directly benefits another through an increased availability of nutrients. In studies of mixed forests, the additional evidence for the occurrence of complementarity has come from radiation absorption studies, i.e. stands with layered canopies which may intercept light more completely than canopies of a single-species. At the canopy level, shade-adapted species tend to have greater total amounts of foliage, per unit land area, and intercept more light than canopies of sun-adapted species, because their efficiency at low light levels allows more foliage to survive in deeper crown layers (ASSMANN, 1970). Evidence for complementarity, in terms of rooting depth, may occur from the differences in depth that will increase the overall use of soil resources. According to KELTY (1992) the facilitation mechanisms that improve nitrogen availability can be observed when the mixtures are used in two different ways: first, in mixtures with enhanced litter decomposition rates, thereby increasing the nitrogen available for tree uptake (BROWN, 1992; KENK, 1992; MORGAN *et al.*, 1992), without changing the total nitrogen levels in the soil-plant system;

second, in mixtures that increase total nitrogen levels in the system using species that fix atmospheric nitrogen through symbiotic association with bacteria, in order to achieve greater stand-level productivity than monocultures (BINKLEY, 2003; BINKLEY *et al.*, 2003). To obtain higher productivity, these interactions, complementarity and facilitation, have to occur simultaneously (KELTY, 2006; PRETZSCH *et al.*, 2010). When these mechanisms occur they reflect the territorial niche species separation in the available resources use.

Let us not forget that there is no evidence that a mixture of randomly selected species would generally out yield a monoculture of the most productive component species (KELTY, 1992). The best species for the lower strata are those that are shade tolerant (ASSMANN, 1970; SMITH, 1986). The stratified canopy reduces the competition between species, since they occupy different niches by capturing light at different intensities and locations within the canopy structure (KELTY, 1992). The dynamics of mixed stands, in addition, are generally far more complicated. They have much more variation in terms of shade tolerance, root and height growth patterns and regeneration capabilities than single-species stands (SMITH, 1986; BURKHART and THAM, 1992; LARSON, 1992). As a consequence more types of competitive interaction occur due to additional variation in tree characteristics (BARTELINK, 1999). Apart from the species involved, stands may differ in terms of the contribution of each species to the mixture, in terms of the age structure of the species and in terms of the stand age and origin (planted or natural regeneration). The pattern of the established trees and the site conditions can also influence interspecies relations (BARTELINK, 1999).

The basic stratified canopy structure in mixtures tends to develop naturally because sun-adapted species generally have greater rates of juvenile height growth than shade species (KELTY, 1992). Properly selected species can be planted simultaneously and the stratified mixture will then develop automatically (SMITH, 1986). The height-growth pattern is one of the most important silvicultural attributes affecting competitive interaction that leads to stratification of the canopy (LARSON, 1992). However it is important to understand the shade tolerance of the species involved in order to better characterize the mechanisms of height-growth patterns.

Development of canopy stratification has been observed in mixed-species plantations established in the past decades, for instance in mixed *Pseudotsuga menziesii* (Mirb.) Franco and *Tsuga heterophylla* (Raf.) Sarg forests in the Pacific Northwest of the United States, where *P. menziesii* overtops *T. heterophylla* in even-aged stands (WIERMAN and OLIVER, 1979). The potential advantage of the stratified canopy in mixed-species stands depends upon the range of sun and shade adaptation among species being greater than that of sun and shape leaf developmental acclimatization within any one species (KELTY, 1992). To manage mixed-species the use of late-succession species in the lower stratum and an early succession species in the upper stratum has been recommended (ASSMANN, 1970; KELTY, 1992).

A combination of shade-tolerant with sun-adapted species might create a multi-layered canopy, which could result in a great radiation interception (BARTELINK, 1999). If this advantage exists a mixed canopy would have greater photosynthetic capacity and the foliage of the sun-adapted species utilizes high intensity light at the top of the canopy more efficiently than the leaves of the shade-adapted species. In this way, the yield of mixed stands can exceed the yields of the monospecific stands of the component species. However, BURKHART and THAM (1999) stated that in most situations the yield of the mixtures will normally be somewhere between the yield of the monocultures of the less productive and the most productive species, because the growing conditions are not optimal for both species.

The choice between pure or mixed stands is often one between pure conifers and mixtures of conifers and hardwoods (BURKHART and THAM, 1992). Generally, conifers have a higher proportion of biomass in the bole than hardwood trees. Conifers are not as sensitive to unfavourable site conditions as hardwoods.

The productivity of large forest areas might be also significantly enhanced by manipulation of the nutrient dynamics of tree mixtures. Mixed-species may reduce nutrient losses and immobilisation in forest soils, because they may lead to the formation of a more favourable humus type (GARDINER, 1999). Different species can be associated to changes in forest floor and influence mineral soil properties due to difference in litter quality, root activity, canopy interception of atmospheric decomposition, growth and nutrient availability (WELKE and HOPE, 2005). Species composition in a stand will influence the amount and chemistry of the inputs into the nutrient cycle and play a major role in plant population dynamics (ANDRÉ *et al.*, 2008). To test for a nutritional involvement in the differential growth of species in pure and mixed stands, foliage has to be chemically analysed for N, P and K and compared between stands. Soil samples should also be collected to be analysed. A substantial proportion of the nutrients taken up during the growing season are returned to the soil through leaf litterfall and are then progressively released during decomposition (ATTIWIL and ADAMS, 1993). On principle, litter of more than one species is expected to reach higher nutrient soil value than litter from pure stands. In nutrient poor ecosystems, this assumption is essential for maintaining chemical fertility. Some studies confirm this assumption and suggest that soil nutrient cycling may be enhanced in mixtures, particularly in mixtures of broadleaves and conifers (ABER and MELILLO, 1991; CHAPMAN *et al.*, 1988; ROTHE and BINKLEY, 2001).

Forests stands in Portugal

Forests cover about 31% of the earth's land surface, approximately 4 billion ha (FAO, 2010), and have been for ages mainly a source of wood. But, in reality, they provide much more than that and their importance in the actual economic and ecological context is growing.

Forests cover almost one third of the European land area, around 193 million ha (Russia excluded), representing 4% of the world's forests (FAO, 2007). According to the last National Forest Inventory (NFI6) forests occupy 35.4% of the Portuguese territory (ICNF, 2013). A characterization of the forestry evolution in Portugal, including the reforestation state subsidized programs that occurred from the 1930's onwards, was made by TOMÉ *et al.* (1999). The forest area almost doubled in the last century as a consequence. The major concerns for the future of the forest and forestry sector in Portugal are wildfires, rural abandonment (emigration to the cities led to forsake management practice), global climate change and desertification (INE, 2001; ROSÁRIO, 2004; DGRF, 2006; PEREIRA *et al.*, 2006).

The economic importance of the forestry sector is well established. Forest ecosystems have a relevant function by providing a great variety of products and a diverse range of regulating services including soil protection, water and air purification and climate regulation. They are a reservoir for a large fraction of the world's plant and animal species (MA, 2005). Nowadays they also have an important role in the global carbon budget.

The most important tree species in Portugal, by area of occupation, are *Eucalyptus globulus* Labill., *Quercus suber* L. and *Pinus pinaster* Aiton with around 72% of the total forest area (ICNF, 2013). *E. globulus* is the main species occupying an area of 812,000 ha. *Q. suber* is the second most important species in terms of area, with 737,000 ha. *P. pinaster* is the third more represented species occupying 714,000 ha of pure, young and dominant mixtures (ICNF, 2013). The private sector owns 84% of the forest land, 14% belongs to local communities and 2% is owned by the state (DGRF, 2006). Most of the forest areas owned by private landowners are not tended properly (TOMÉ *et al.*, 1999).

Around 84% of the total area of forests consists of pure stands (AFN, 2010). Economic reasoning has been decisive in the move towards pure stands. These are mostly composed by *P. pinaster* (28%) and *E. globulus* (23%), in the central and northern parts of Portugal. The primary objective was to produce timber and paper pulp to supply the demands of the market. This is not exclusive to Portugal. The genera *Pinus spp.* and *Eucalyptus spp.* dominate plantations around the world, with 20% and 10%, respectively (FAO, 2001b). According to FAO (2001b) managed monocultures supply up to 35% of the global round-wood. This is a consequence of the world's population growth and the wood requirement by the economic agents for building, firewood, paper, etc (WEST, 2006). With most of the emphasis in commercial timber production, the single-species plantations, because of their easier management, became common. Nevertheless the increase in single-species plantations was one of the main points of dispute between foresters and conservationists (RACKHAM, 1992; WEST, 2006).

In Portugal the area of forests with more than one species is around 16% (AFN, 2010), however, in the last decades, the importance of mixed stands has been recognized and it is growing (LUÍS, 1997; TOMÉ *et al.*, 1999; GONÇALVES *et al.*, 2010). In the north and center of Portugal the more common mixed-species stands have mainly *P. pinaster* as the dominant species (AFN, 2010). In the south, mixed stands occupy a much smaller area and are generally dominated by *Q. suber* or evergreen oaks (AFN, 2010). Yet the data on structure, composition, growth and yield of mixed stands are scarce and difficult to obtain. This underlines the need for accurate information to support mixed forest management.

Based on the NFI 2005/06, GODINHO-FERREIRA *et al.* (2010) reached the conclusion that in Portugal there is small diversification in forest stands, the dominant species being merely one or two. The analysis of diversity in forest stands was performed by evaluating the percentage of the species basal area using the NFI of 1995 and 2005 data. The results also show a tendency for higher diversity in regions close to the sea, where the dominant species are *P. pinaster* and *E. globulus*. These species got mixed together probably as a consequence of natural regeneration due to lack of management or after wildfires.

Research on mixed-species forests in Portugal

Mixed stands, whether they are naturally regenerated or installed through sowing or planting are, nowadays, an important objective in forest management. Silvicultural techniques applied to mixed-species forest are widely developed and modernized in countries such as German and Switzerland, due to many years of study in permanent plots and the ongoing management of these stands. The situation in Portugal is different; the scientific knowledge about mixed-species stands productivity is, in general, still poor. Nevertheless this knowledge is essential to evaluate productivity and the economic viability of these stands when compared with pure ones. There is also a need to clarify what type of mixture is required, more information on site conditions, better understanding of the growth rate of the species; all these factors are indispensable in the management of mixed stands (KENK, 1992).

MONTEIRO ALVES (1988) reached the conclusion that the establishment and management of mixed plantations should be a major objective of investigation and, in that way, help to close conflicts between production and protection of resources. In fact, these potential conflicts between production and protection of resources are well integrated in various forestry models, including those developed in the framework of ProSilva, a federation of professional foresters, founded in 1999 (https://prosilvaeurope.wordpress.com/).

In Portugal, for a stand to be defined as mixed, it must contain a dominant species that complies with the following conditions: a maximum percentage of 75% of occupation in the stand (DGSFA, 1968; DGF, 2001), a maximum of 90% of the total number of individuals per hectare and no more than 75% of the basal area (LUÍS, 1997). There are four main types of mixed-species stands identified by TOMÉ *et al.* (1999): existing mixed-species stands; conversion of pure stands into mixed stands, mixed-species plantations and mixed-species experimental trials. Table 1 presents a summary of species in mixed situations related to the four main types of stands.

In the next section, according to this classification, there is a description of studies already done or in the process of completion about mixed plantations in Portugal. The objective is to present, as much as possible, the available data from various sources to give the perception of the importance of mixed-forests in Portuguese forestry. To further the investigation and information about mixed-species plantations there was also a government project: *Florestas mistas. Modelação, dinâmica e distribuição geográfica da produtividade e da fixação do carbono nos ecossistemas florestais mistos em Portugal. Projecto PTDC/AGR-CFL/68186/2006 da*

Fundação para a Ciência e a Tecnologia. This project covered most of the country and type of forests in Portugal.

***Table 1** - A summary of mixed-species research in Portugal*

Types of stands	Species	Establishment	Location	References
Existing mixed-species stands	*Quercus pyrenaica* *Pinus pinaster*	Natural regeneration	Northern Portugal: Vila Real district	NUNES *et al*. (2013); MENDES (2011)
	Mixed broadleaf species	Natural regeneration due to the process of abandonment of agriculture lands	Northern Portugal: Aboboreira, Castelo and Marão mountains	ROXO and BENTO (2010)
	Quercus pyrenaica *Quercus rotundifolia*	Natural regeneration	Northeastern Portugal: Tapada da Nogueira (Bragança district)	REGO *et al*. (2011)
	Acer pseudoplatanus *Betula celtiberica* *Castanea sativa* *Chamaecyparis lawsoniana* *Pinus pinaster* *Pinus sylvestris* *Quercus rubra*	Artificial regeneration	Northwestern Portugal: Mezio in Peneda-Gerês National Park	SEQUEIRA and CARVALHO OLIVEIRA (1994)
	Quercus rubra *Quercus robur* *Betula celtiberica*	Plantation	Northwestern Portugal: Arcos de Vadevez	FERREIRA (1996)
	Pinus pinaster *Quercus suber*	Natural regeneration	Center Portugal: Casal das Balsas	COELHO (1996); INÁCIO (1998)
	Pinus pinaster *Acacia melanoxylon* *Acacia longifolia*	Natural regeneration	Northwestern Portugal: Camarido National Forest	BENTO and MAGALHÃES (2010)
Pure stands converted to mixed stands	*Pinus pinaster* *Castanea sativa* *Quercus robur* *Other conifers and broadleaf species*	Artificial regeneration (by seedling)	Center Portugal: Cantão das Hortas, Lousã	CARVALHO OLIVEIRA (1992); PINTO da COSTA (1992); PINTO da COSTA and PREUHSLER (1994); GONÇALVES (2003); GONÇALVES and CARVALHO OLIVEIRA (2011); GONÇALVES *et al*. (2010)
	Mixed broadleaf species	Natural regeneration	Center Portugal: Serra do Caramulo	LUÍS (1997)
Mixed-species plantations	*Pseudotsuga menziesii* *Castanea sativa* and *Castanea sativa* *Pinus pinaster*	Plantation	Northeastern Portugal: Sta. Comba de Rossas (Bragança district)	FERNADES (1996)
	Pinus pinaster *Pinus pinea*	Plantation	Center Portugal: Mata Nacional das Virtudes (Azambuja, Santarém district)	LOPES (1997)
	Quercus suber *Pinus pinea or Pinus halepensis* and *Quercus suber* *Cerotonia siliqua*	Plantation	South Portugal: Castro Marim	AMARAL (1992)

Table 1 *– Cont.*

Types of stands	Species	Establishment	Location	References
Mixed-species experimental trials	*Castanea sativa* *Pseudotsuga menziesii*	Experimental plantation	Northeastern Portugal: Bemlhevai (Bragança district)	MAIA (1988); JORDÃO (1993); SARAIVA (1993); LUÍS and MONTEIRO (1998); MONTEIRO *et al.* (1994); NUNES *et al.* (2011); NUNES *et al.* (2014)
	Prunus avium *Juglans nigra* *Fraxinus excelsior* *Alnus cordata*	Experimental plantation	Northeastern Portugal	MONTEIRO (1991); PEREIRA *et al.* (2008); MONTEIRO *et al.* (2009)
	Punus avium *Quercus rubra* *Castanea sativa* *Robinia pseudoacacia*	Experimental plantation	Northeastern Portugal	MONTEIRO (1991); PATRÍCIO *et al.* (2010); PEREIRA *et al.* (2011)
	Castanea sativa *Pseudotsuga menziesii*	Experimental plantation	Northeastern Portugal	FONSECA *et al.* (2011)
	Quercus suber *Quercus rotundifolia* *Pinus pinaster* *Pinus pinea*	Experimental plantation	South Portugal: Mata do Cabeção, Qta. Cabeça Gorda and Herdade da Mitra	TOMÉ *et al.* (1999)

Permanent mixed stands

This is the most common type of mixed-species stands in Portugal. These stands may have been naturally, or with human influence, or yet artificially regenerated by seeding or planting during the early afforestation programs in the 1930's and 1940's (TOMÉ *et al.*, 1999). There are several mixtures in Portuguese stands and they differ from the North (hardwoods and conifers and in the mountainous regions of the Center) to the South (*P. pinaster*, *Pinus pinea* L. and *Q. suber*, or *Q. suber* and evergreen oaks). *P. pinaster* and *Eucalytus* spp. mixtures also occur elsewhere in the Center. Some compiled examples:

i. Mixed *P. pinaster* and *Quercus pyrenaica* Willd. stands study in the Vila Real district to analyze and compare their growth and productivity to pure *P. pinaster* and *Q. pyrenaica* (NUNES *et al.*, 2013). This study used a set of 15 *P. pinaster* stands, 15 *Q. pyrenaica* stands and 9 mixed ones that were selected from the Portuguese National Forest Inventory. These stands are located in private land, most of them are of small size and were naturally regenerated. Biomass equations were derived, at tree level, for aboveground components and total aboveground biomass of *P. pinaster* and *Q. pyrenaica* (MENDES, 2011). These equations allow biomass estimation based on information from conventional forest inventories. The sampling plots average tree height was calculated and trees with these dimensions were identified nearby in the National Forest

Inventory plots to collect individual tree biomass data. Using the destructive method, 36 trees (21 *P. pinaster* and 15 *Q. pyrenaica*) were harvested and all aboveground components (needles/leaves, stem and branches) were separated and weighted. The equations were simultaneously fitted using seemingly unrelated regression. These equations relate biomass dry weight with perimeter at the breast height (cm) and total height (m) of the tree. Results indicate higher productivity in mixed stands than *P. pinaster* and *Q. pyrenaica*. Also, the production efficiency, defined as stem productivity/leaf area index, was significantly different in mixed stands when compared with pure ones.

ii. In lands previously used to agriculture, in northern Portugal, and now in a process of abandonment, new mixed hardwood-species stands had been growing by natural regeneration (ROXO and BENTO, 2010). The study has been carried out for 15 years in an area of 20,000 ha across the Aboboreira, Castelo and Marão mountains. The area was characterized in terms of tree species diversity, structure/age distribution and spatial dispersion. In 2010 the composition of nearly 15% of the existing area was mixed hardwood stands. The tree composition represents the initial characteristics of mixed hardwood species. The main species are *Q. pyrenaica*, *Quercus robur* L., *Castanea sativa* Mill. and *Populus* sp. The evolution of the mixed hardwood stands, when compared with the initial land use (1958), indicates that the last 15 years were relevant for the present situation.

iii. Mixed stands analysis of *Q. pyrenaica* and *Quercus rotundifolia* Lam. was carried out in Tapada da Nogueira, Bragança region (REGO *et al.*, 2011). The study was based on Forest Inventory plots from Tapada da Nogueira. These two abundant species have variable area stands in this zone. Results of field measurements indicated a predominance of small diameters in both species, and the class with an average of 10 cm diameter at breast height exhibiting the larger frequency. The highest values of basal area are in the mixtures, probably because the mixtures have the better occupation of the available space and soil horizons. Flexible models of space organization were proposed, to be used in forestry timber production and other forest uses like deer hunting, which is made possible by the walled area of the Tapada.

iv. Based on forest inventory data, a management plan was developed in order to change the orientation of the stands in the Mezio forest, the objective being the promotion of mixed stands with a stratified canopy and thus breaking the continuity of the coniferous cover (SEQUEIRA and CARVALHO OLIVEIRA, 1994). The study also aimed to establish a network of permanent plots to monitor the behaviour of the stands object of the applied silvicultural treatments. This forest is located in the Peneda-Gerês National Park, northwestern Portugal, and has an area of 570 ha at an altitude between 400 and 800 m. The Mezio forest was artificially regenerated by a national reforestation program, which took place between the thirties and the fifties. This program was to be applied in the northern and central mountain areas of the country, which were in a high level of degradation at that stage. The main species utilized were *Acer pseudoplatanus* L., *Betula celtiberica* Rothm. & Vasc., *C. sativa*, *Chamaecyparis lawsoniana* (Al. Murray) Parl., *P. pinaster*, *Pinus sylvestris* L. and *Quercus rubra* L.

v. Academic studies done by undergraduates on the subject of mixed plantations: FERREIRA (1996) described a planted, even-aged, 42 years-old stand, located in Arcos de Valdevez, also in the northwest of Portugal but at lower latitude than the forest of Mezio, the main species were *Q. rubra*, *Q. robur* and *B. celtiberica*; COELHO (1996) and INÁCIO (1998) characterized the Casal das Balsas forest located in the center of Portugal, as an uneven-aged, mixed forest of *P. pinaster* and *Q. suber*.

vi. Stands characteristics, such as age, composition and structure has been analysed in the Camarido National Forest, a public forest located in the northwest of Portugal. The stands are occupied by pine, dating from the Middle Ages, and acacias (*Acacia melanoxylon* R. Br. and *Acacia longifolia* (Andrews) Willd), that were planted in the beginning of the 20th century. The development and natural regeneration of both pine and acacia species in mixed plots have been observed in order to evaluate the influence of the relative interspecific competition and its effects on pine tree forms (BENTO and MAGALHÃES, 2010). The evaluation of the tree form has been done according to the height/diameter ratio.

Pure stands converted to mixed stands

This stand type results from the promotion of natural regeneration under pure stands shelters to gradually transform them into mixed-species stands or even into pure broadleaf stands according to site quality (TOMÉ *et al.*, 1999). These transformations and their success are very dependent on the forester because he has here a very important role to play. As the pure *P. pinaster* stands, regenerated in the 1940's and 1950's, approach rotation age, the trend in this type of stand is increasing and a variety of silvicultural interventions have been promoting the gradual change of pure *P. pinaster* stands to stratified levels mixed ones.

i. A set of twenty-two permanent plots in Lousã, a mountainous area in the center of Portugal, started to be monitored in 1988 under the project "Biometrical and silvicultural Research for mixed stands in Portugal", supported by the Alexander von Humboldt Foundation (Bonn) and by the *Centro de Estudos Florestais* (INIC) in Portugal. The forest known as *Cantão das Hortas* has some good examples of pure *P. pinaster* stands regenerated by seedling in the 1940's. The plots had no experimental design and were implemented in carefully chosen sites to estimate the forest dynamics (CARVALHO OLIVEIRA, 1992). They were characterized in terms of structure, growth and yield (PINTO da COSTA, 1992; PINTO da COSTA and PREUHSLER, 1994). The plots were composed by *P. pinaster* with an understory of *C. sativa*, *Q. robur* and younger *P. pinaster*. Cuttings were carried out, after the first measurement, in order to promote a transformation process towards the increase of broadleaf species. The low intensity cuttings removed mainly *P. pinaster* individuals. Of the total area about 12.1% are pure stands and 40.1% are mixed with *C. sativa*. Other softwood and hardwood species are also present in pure or mixed stands, namely *P. menziesii*, *Cupressus lusitanica* Miller, *C. lawsoniana*, *Q. robur*, *Q. rubra*, *Prunus avium* L., *Fagus sylvatica* L. and *E. globulus* (GONÇALVES, 2003). A characterization of the existing natural regeneration and their evolution was made by two successive measurements in 2001 and 2009 (GONÇALVES and CARVALHO OLIVEIRA, 2011). This was done in order to analyze the stand density, regeneration diversity and recruitment in *P. pinaster* old growth stands with natural regeneration of several broadleaf species, in particular *C. sativa* and *Q. robur*. Results revealed an increase in the number and dimensions of *C. sativa* and *Q. robur*. These stands are still in a transformation process from pure to mixed formations (GONÇALVES *et al.*, 2010). The cuttings originated an increase of *C. sativa* and *Q. robur*, both due to the removal of *P. pinaster* and the recruitment of individuals of those two species. Diversity indices were used to characterize the horizontal, vertical and spatial distribution of the individuals in the multi-species stands (GONÇALVES *et al.*, 2010). Diversity dynamics were evaluated by two successive measurements, in 2001 and 2009. With time this study is expected to give a better knowledge of these stands growth dynamics.

ii. There is also in Serra do Caramulo, in the center of Portugal, a gradual conversion to mixed plantations with local well adapted broadleaf species (LUÍS, 1997). No more information is available from this site.

Mixed-species plantations

These plantations were purposely planted as mixed stands, in anticipation of some advantage from the mixtures, during several afforestation programs that began in the 1970's (TOMÉ *et al.*, 1999). In the north these plantations usually associated a coniferous species with a broadleaf species, like *P. menziesii* and *C. sativa* or *P. pinaster* and *C. sativa*. In the south, they associated *Q. suber* and *P. pinea* or *Pinus halepensis* Miller.

i. In Sta. Comba de Rossas, Bragança district, in northeastern Portugal, a mixed-species plantations of *C. sativa* and *P. pinaster* was established in 1971 and FERNANDES (1996) made the description of these plantations.

ii. In Mata Nacional das Virtudes, Azambuja, were established in 1955 plantations of various species including *P. pinaster* and *P. pinea*; a large part of these are mixed plantations and they were surveyed to characterize the species growth (LOPES, 1997).

iii. Analysis of mixed stands of *Q. suber* and coniferous (*P. pinea* or *P. halepensis*), and *Q. suber* and *Ceratonia siliqua* L. were made in the south of the country, in Castro Marim (AMARAL, 1992). These plantations were established in the 1960's in a degraded, semi-arid site. *Q. suber* is a very important species in this region because of economic, social and ecologic reasons. These forests are particularly fragile as a result of human pressure.

Mixed-species experimental trials

Mixed plantations were established with the objectives of obtaining information and a better understanding on this type of stands. Long term monitoring is essential to be able to select, in the future, the mixtures that have the best results in terms of growth and yield.

i. In 1981, a set of twenty-one permanent research plots were planted on private land at Bemlhevai, Bragança (northeastern Portugal), in mixed stands of

C. sativa and *P. menziesii* (LUÍS and MONTEIRO, 1998; MAIA, 1988; MONTEIRO *et al.*, 1994). This was the first mixed experimental plantation in Portugal. The trial is 'substitutive', with a complete randomised block design using seven consociation types, three replications and 64 plants in each plot. The research plots were installed to analyse the growth and potential productivity of both species in single and mixed-species plots. The first data evaluation was made for height, basal area at 0.3 m and volume (MAIA, 1988). During the development of the research plots some academic studies were done (JORDÃO, 1993; SARAIVA, 1993). Recent results of growth and productivity patterns in this experimental site are presented in NUNES *et al.* (2014). A study to analyse soil and foliar properties was also carried out (NUNES *et al.*, 2011).

ii. An experimental trial, with the support of Project PRAXIS XXI - 3/3.2/Flor/2127/95, was established in 1988 in abandoned lands in the northeast of Portugal (MONTEIRO, 1991; MONTEIRO *et al.*, 2009). This study has mixed permanent plots of broadleaf species, to produce high quality timber, with N-fixing species. 36 plots with 12 different treatments and 3 replications of the following species were established: *P. avium*, *Juglans nigra* L., *Fraxinus excelsior* L. and *Alnus cordata* (Loisel.) Duby. The objective of this study was to analyse the growth response of the valuable timber tree species in the presence of the N-fixing species. Field measurements, such as diameter at breast height, height and survival, were done in order to characterize the trial and to analyse the behaviour of all the plots. The dynamic evaluation of soil N was done by sequential incubation in situ to evaluate the availability of nitrogen on the soil, and also its effect on the species (PEREIRA *et al.*, 2008). Results indicate better diameter and height growth in these valuable timber species with the presence of N-fixing trees.

iii. Within the framework of the Project PRAXIS XXI – 3/3.2/Flor/2127/95, also in the north of the country, a mixture plantation trial with valuable broadleaf tree species: *P. avium*, *Q. rubra* and *C. sativa* with the accessory species *Robinia pseudoacacia* L., was established in 1998 in a substitutive or replacement series design (MONTEIRO, 1991; PATRÍCIO *et al.*, 2010). A completely random experimental design of 30 permanent sample plots with 10 treatments and 3 replications was adopted and two types of mixtures were considered (alternating lines of the target-species with *R. pseudoacacia* and target-species alternating with *R. pseudoacacia* in the line). According to PATRÍCIO *et al.* (2010) the aim of the study was to evaluate the benefits to the target-species when mixed with a nitrogen-fixing species. These authors observed a facilitation effect promoted by the accessory species on the *P. avium* trees. For *Q. rubra* and *C. sativa* species a depressive effect of *R. pseudoacacia* on the target-species was observed in the intimate mixture situation, causing the facilitation effect to be not so obvious. Besides this study another one was carried out to better understand the effect of *R. pseudoacacia* consociation with *P. avium* (PEREIRA *et al.*, 2011). In each plot were measured soil N mineralization dynamics, soil microbial biomass carbon and nitrogen, microbial quotient, metabolic quotient, microbial respiration and dehydrogenase activity. The authors observed a positive impact of *R. pseudoacacia* on the supply of nitrogen to the soil. The net N-mineralization rates were about three times greater in pure *R. pseudoacacia* than in pure *P. avium* and about two times greater in mixture than in pure *P. avium*. Soil microbial biomass carbon and cumulative soil respiration were higher in mixture than in pure *P. avium* plantation soil, which may reflect positive changes in the soil environment. More studies are needed to confirm assumptions such as vigour and resistance to diseases, as well as the processes of facilitation and complementarity in order to better understand the benefits of this consociation (PEREIRA *et al.*, 2011).

iv. In a newly installed mixed forest stand in the northeast of Portugal, as part of a wider project, an experimental plantation was studied by FONSECA *et al.* (2011). The effect of several site preparation techniques on plant survival and growth (height and diameter) were tested. This experimental protocol consisted in seven treatments described by mechanical operations that rank soil disturbance intensity from nil to high, set in plots of 375 m^2, randomly distributed in three blocks, in different topographic positions (gentle slope plateau, moderate slope shoulder, and steep mid-slope). The species studied were *P. menziesii* and *C. sativa*, planted in a 4 × 2 m scheme and in alternate rows with 12 trees on each row per plot, summing up 72 trees per species and treatment at the start of the experiment.

v. Four trials were established to study methods and adequate stand composition for the afforestation of former agricultural lands in the south of Portugal. These trials are located in: Mata do Cabeção (2 trials), Qta. Cabeça Gorda and Herdade da Mitra (TOMÉ *et al.*, 1999). The species used in these trials were *Q. suber*, *Q. rotundifolia*, *P. pinaster* and *P. pinea*. No more information is available from these trials.

Conclusion

The importance of studies in mixed-species is nowadays recognized worldwide. In Portugal, from the data available, mixed-species forests were mainly established spontaneously, by natural regeneration processes. The interest in purpose made mixed plantations has increased greatly in the past decades due to ecological considerations and potential economic benefits, especially in conifer-broadleaves mixtures. In order to obtain a higher productivity the specific combination of species has to be chosen and studied carefully.

To support the creation and management of these forests more studies are necessary on growth and productivity in mixed-species stands in Portugal. They should provide a better knowledge of key parameters, like net primary production, and help to understand the performance and growth dynamics of mixed forests.

The research, in naturally regenerated as well in planted forests, should include also both production and environmental targets.

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References

ABER, J.D., MELILLO, J.M., 1991. *Terrestrial Ecosystems*. Saunders College Publishing. Phildelphia, p. 429.

AFN, 2010. *Inventário Florestal Nacional, Portugal Continental - IFN5 2005-2006.* Relatório Final. Autoridade Florestal Nacional, Lisboa, p. 209.

AMARAL, M.R.J.F., 1992. *Arborizações em Áreas Degradadas*. Relatório de Estágio do Curso de engenheiro Silvicultor, Instituto Superior de Agronomia, Lisboa, p. 70.

ANDRÉ, F., JONARD, M., PONETTE, Q., 2008. Spatial and temporal patterns of throughfall chemistry within a temperate mixed oak-beech stand. *Sci. Total Environ*. **397**: 215-228.

ASSMANN, E., 1970. *The principles of forest yield study*. Pergamon Press, Oxford, p. 506.

ATTIWILL, P.M., ADAMS, M.A., 1993. Tansley Review No. 50: Nutrient cycling in forests. *New Phytologist* **124**: 561-582.

BALL, J.B., WORMALD, T.J., RUSSO, L., 1995. Experience with mixed and single species plantations. *Commonwealth Forestry Review* **74**: 301-305.

BARTELINK, H.H., 1999. *Growth and management of mixed-species stands*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., FRANC, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 187-190.

BARTELINK, H.H., 2000. A growth model for mixed forest stands. *For. Ecol. Manage.* **134**: 29-43.

BARTELINK, H.H., OLSTHOORN, A.F.M., 1999. *Introduction: mixed forest in western Europe*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., FRANC, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 9-16.

BENTO, J., MAGALHÃES, M., 2010. *Specific tree form coefficients in mixed stands*, in: LOPES, D., TOMÉ, M., LIBERATO, M., SOARES, P. (Eds.), IUFRO conference Mixed and Pure Forests in a Changing World, Vila Real, Portugal, p. *Abst* 33.

BINKLEY, D., 2003. Seven decades of stand development in mixed and pure stands of conifers and nitrogen-fixing red alder. *Can. J. For. Res.* **33**: 2274-2279.

BINKLEY, D., RYAN, M.G., 1998. Net primary production and nutrient cycling in replicated stands of *Eucalyptus saligna* and *Albizia facaltaria*. *For. Ecol. Manage.* **112**: 79-85. doi: 10.1016/S0378-1127(98)00331-4.

BINKLEY, D., SENOCK, R., BIRD, S., COLE, T.G., 2003. Twenty years of stand development in pure and mixed stands of *Eucalyptus saligna* and N-fixing *Facaltaria moluccana*. *For. Ecol. Manage*. **182**: 93-102. doi: 10.1016/S0378-1127(03)00028-8.

BMELV, 2011. *German forests: Nature and economic factor*. Federal Ministry of Food, Agriculture and Consumer Protection. German.

BOUDRU, M., 1986. *Forêt et Sylviculture: sylviculture appliquée*. Presses Agronomiques, Gembloux, Belgium.

BROWN, A.H.F., 1992. *Functioning of mixed-species stands at Gisburn, N.W.* England, in: CANNELL, M.G.R., MALCOLM, D.C., ROBERTSON, P.A. (Eds.), The Ecology of Mixed-Species Stands of Trees. Blackwell, London, pp. 125-150.

BURESTI, E., FRATTEGIANI, M., 1994. *First results of a mixed plantation with high quality timber broadleaves and N-fixing trees*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, pp. 219-228.

BURKHART, H.E., THAM, Å., 1992. *Predictions from growth and yield models of the performance of mixed-species stands*, in: CANNELL, M.G.R., MALCOLM, D.C., ROBERTSON, P.A. (Eds.), The Ecology of Mixed-Species Stands of Trees. Blackwell, London, pp. 21-34.

CARVALHO OLIVEIRA, A.M.M., 1984. *Teoria da Produção Florestal*. 2ª Ed. Centro de Estudos Florestais, Lisboa, p. 531.

CARVALHO OLIVEIRA, A., 1992. *Research Projects on Mixed Stands in Portugal*, in: PREUHSLER, T. (Ed.), Research on Growth and Yield with Emphasis on Mixed Stands. Proceedings of IUFRO Centennial Meeting. Sessions S4.01 "Mensuration, Growth and Yield'. Published by the Bavarian Forest Experiment Station and University of Munich, Freising, Germany, pp. 11-17.

CHAPMAN, K., WHITTAKER, J.B., HEAL, O.W., 1988. Metabolic and faunal activity in litters of tree mixtures compared with pure stands. *Agric. Ecosyst. Environ*. **24**: 33-40.

CHEN, H.Y.H., POPADIEUK, R.V., 2002. Dynamics of North American boreal mixedwoods. *Environ. Rev.* **10**: 137-166.

CHEN, H.Y.H, KLINKA, K., 2003. Aboveground productivity of western hemlock and western redcedar mixed-species stands in southern coastal British Columbia. *For. Ecol. Manage.* **184**: 55-64.

COELHO, M.B., 1996. *Inventário Florestal de um Povoamento Misto Irregular de Pinheiro Bravo e Sobreiro Situado no Concelho da Chamusca*. Relatório Fim de Curso em Engenharia Florestal, Instituto Superior de Agronomia/UTL, Lisboa, p. 81.

CUMMING, S.G., 2001. Type and wildfire in the Alberta boreal mixedwood: what do fires burn? *Ecol. Appl.* **11**: 97-110.

de BELL, D.S., COLE, T.G., WHITESELL, C.D., 1997. Growth, development, and yield in pure and mixed stands of *Eucalyptus* and *Albizia*. *For. Sci.* **43**: 286-298.

del RÍO, M., PRETZSCH, H., ALBERDI, I., BIELAK, K., BRAVO, F., BRUNNER, A., CONDÉS, S., DUCEY, M.J., FONSECA, T., von LÜPKE, N., PACH, M., PERIC, S., PEROT, T., SOUIDI, Z., SPATHELF, P., STERBA, H., TIJARDOVIC, M., TOMÉ, M., VALLET, P., BRAVO-OVIEDO, A., 2016. Characterization of the structure, dynamics, and productivity of mixed-species stands: review and perspectives. *Eur. J. Forest Res*. DOI 10.1007/S10342-015-0927-6.

DGF - Direcção Geral das Florestas, 2001. *Inventário Florestal Nacional Portugal Continental, 3ª Revisão, 1995-1998.* Lisboa. Portugal.

DGRF - Direcção Geral dos Recursos Florestais, 2006. *Estratégia Nacional Para as Florestas*. Lisboa, p. 189.

DGSFA - Direcção Geral dos Serviços Florestais e Aquícolas, 1968. *Inventário Florestal.* DGSFA, Lisboa.

DIXON, R.K., MELDAHL, R.S., RUARK, G.A., WARREN, W.G. (Eds.), 1990. *Process Modeling of Forest Growth Responses to Environmental Stress*. Timber Press, Portland, p. 441.

FAO, 1988. *Forest policies in Europe*. FAO Forestry Paper 86. p. 286.

FAO, 2001a. *State of the world's forest 2001*. Food and Agriculture Organization of the United Nations, Rome.

FAO, 2001b. *Global Forest Resources Assessment 2000*. Main Report. FAO Forestry Paper 140, Food and Agriculture Organization of the United Nations, Rome, p. 479.

FAO, 2007. *State of the world's forest 2007*. Food and Agriculture Organization of the United Nations, Rome, p. 144.

FAO, 2010. *Global Forest Resources Assessment 2010*. Main report. FAO Forestry Paper 163, Food and Agriculture Organization of the United Nations, Rome, www.fao.org/docrep/013/i1757e/i1757e00.htm.

FERNANDES, J.P., 1996. *Estabelecimento de Parcelas Permanentes num Povoamento Misto de Castanea sativa e Pinus pinaster no Concelho de Bragança*. Relatório Fim de Curso em Engenharia Florestal, Instituto Superior de Agronomia/UTL, Lisboa.

FERREIRA, S.V., 1996. *Contribuição para o Estudo da Quercus rubra L. em Povoamentos Mistos.* Análise de Parcelas Permanentes no Concelho de Arcos de Valdevez. Relatório Fim de Curso em Engenharia Florestal, Instituto Superior de Agronomia/UTL, Lisboa, p. 93.

FONSECA, F., FIGUEIREDO, T., MARTINS, A., 2011. Survival and early growth of mixed forest stands installed in a Mediterranean Region: Effects of site preparation intensity. *For. Ecol. Manage.* **262**: 1905-1912.

FOREST EUROPE, UNECE and FAO, 2011. *State of Europe's Forests 2011*. Status and trends in sustainable forest management in Europe. 337 (MCPFE. Forest Europe Liasion Unit Oslo: 2011).

FORRESTER, D.I., BAUHUS, J., KHANNA, P.K., 2004. Growth dynamics in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. *For. Ecol. Manage*. **193**: 81-95. doi: 10.1016/j.foreco.2004.01.024.

FORRESTER, D.I., BAUHUS, J., COWIE, A.L., 2006a. Carbon allocation in a mixed-species plantation of *Eucalyptus globulus* and *Acacia mearnsii*. *For. Ecol. Manage.* **233**: 275-284. doi: 10.1016/j.foreco.2006.05.018.

FORRESTER, D.I., COWIE, A.L., BAUHUS, J., Wood, J., FORRESTER, R.I., 2006b. Effects of changing the supply of nitrogen and phosphorus on growth and interactions between *Eucalyptus globulus* and *Acacia mearnsii* in a pot trial. *Plant Soil* **280**: 267-277. doi: 10.1007/s11104-005-3228-x.

FRIEDRICH, J.M., DAWSON, J.O., 1984. Soil nitrogen concentration and *Juglans nigra* growth in mixed plots with nitrogen-fixing *Alnus*, *Elaeagnus*, *Lespedeza*, and *Robinia* species. *Can. J. For. Res.* **14**: 864-868.

FRIVOLD, L.H., GROVEN, R., 1996. Yield and management of mixed stands of spruce, birch and aspen, in: DIETRICHSON, J. (Ed.), Silviculture for fuelwood. *Norwegian Journal of Agricultural Science* **24**: 21-28.

FRIVOLD, L.H., KOLSTRÖM, T., 1999. *Yield and treatment of mixed stands of boreal tree species in Fennoscandia*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., FRANC, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 37-45.

GARDINER, J.J., 1999. *Changing forests, management, and growing*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., Franc, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 17-19.

GOBAKKEN, T., NAESSET, E., 2002. Spruce diameter growth in young mixed stands of Norway spruce (*Picea abies* (L.) Karst.) and birch (*Betula pendula* Roth *B. pubescens* Ehrh.). *For. Ecol. Manage*. **171**: 297-308.

GODINHO-FERREIRA, P., AZEVEDO, A., REGO, F.C., 2010. Alteração da Diversidade de Espécies Arbóreas nos Povoamentos Florestais entre 1995 e 2005 (Portugal Continental*). Silva Lusitana* (Número Especial): Florestas Mistas, pp. 39-50.

GONÇALVES, A.C., 2003. *Modelação de povoamentos adultos de pinheiro bravo com regeneração de folhosas na Serra da Lousã*. Doctoral Thesis. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Lisboa.

GONÇALVES, A.C., CARVALHO OLIVEIRA, A., 2011. Regeneration in multi-species in Serra da Lousã. *For. Syst.* **20**(3): 444-452.

GONÇALVES, A.C., CARVALHO OLIVEIRA, A., DIAS, S.S., 2010. Evolution in multi-species high forest stands in Serra da Lousã: diversity analysis. *Silva Lusitana* (Número Especial): Florestas Mistas, pp. 79-90.

HARPER, J.L., 1977. *Population Biology of Plants*. Academic Press, New York.

ICNF, 2013. IFN6 – *Áreas dos usos do solo e das espécies florestais de Portugal continental. Resultados preliminares*. [pdf], 34 pp, Instituto da Conservação da Natureza e das Florestas. Lisboa.

INÁCIO, A.M.M., 1998. *Análise produtiva de povoamentos puros de pinheiro bravo e de povoamentos mistos de pinheiro bravo e de sobreiro situados no Casal das Balsas*. Instituto Politécnico de Castelo Branco. Escola Superior Agrária. Castelo Branco.

INE, 2001. *Recenseamento Geral da População e Habitação (Resultados Definitivos).* Instituto Nacional de Estatística, Lisboa.

JOHANSSON, T., 2003. Mixed stands in Nordic countries - a challenge for the future. *Biomass Bioenerg*. **24**: 365-372.

JORDÃO, M.F., 1993. *Análise de um Ensaio de Consociação de Pseudotsuga menziesii (Mirb.) Franco e Cstanea sativa Miller, no Nordeste Transmontano.* Rel. Fim de Curso. Ges. Rec. Nat. IPB. ESA. Bragança, p. 43.

KAYE, J.P., RESH, S.C., KAYE, M.W., CHIMMER, R.A., 2000. Nutrient and carbon dynamics in a replacement series of *Eucalyptus* and *Albizia* trees. *Ecology* **81**: 3267-3273.

KEENAN, R.J., LAMB, D., SEXTON, G., 1995. Experience with mixed species rainforest plantations in north Queensland. *Commonwealth Forestry Review* **74**: 315-321.

KELTY, M.J., 1989. Productivity of New England helmlock/hardwood stands as affected by species composition and canopy structure. *For. Ecol. Manage.* **28**: 237-257.

KELTY, M.J., 1992. *Comparative productivity of monocultures and mixed species stands*, in: KELTY, M.J., LARSON, B.C., OLIVER, C.D. (Eds.), The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 125-141.

KELTY, M.J., 1994. *Ecological principles of production differences between monocultures and mixtures*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, pp. 15-29.

KELTY, M.J., 2006. The role of species mixtures in plantation forestry. *For. Ecol. Manage.* **233**: 195-204.

KENK, G.K., 1992. *Silviculture of mixed-species stands in Germany*, in: CANNELL, M.G.R., MALCOLM, D.C., ROBERTSON, P.A. (Eds.), The Ecology of Mixed-Species Stands of Trees. Blackwell, London, pp. 53-63.

KINT, V., GEUDENS, G., MOHREN, G.M.J., LUST, N., 2006. Silvicultural interpretation of natural vegetation dynamics in ageing Scots pine stands for their conversion into mixed broadleaved stands. *For. Ecol. Manage*. **223**: 363-370.

KRAMER, H., 1994. *Investigations of Stem Development and Growth in Even-Aged and Uneven-Aged Coniferous Stands by Stem Analysis*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, pp. 105-121.

LARSON, B.C., 1992. *Pathways of development in mixed-species stands*, in: KELTY, M.J., LARSON, B.C., OLIVER, C.D. (Eds.), The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 125-141.

LAVIGNE, M.B., 1992. *Exploring the possibilities of developing a physiological model of mixed stands*, in: KELTY, M.J., LARSON, B.C., OLIVER, C.D. (Eds.), The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 125-141.

LEIKOLA, M., 1999. *Definition and classification of mixed forests, with a special emphasis on boreal forests*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., Franc, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 20-28.

LOPES, H.M.J., 1997. *Plano de Gestão das Matas Nacionais das Virtudes e do Escaroupim*. Relatório Final de Estágio, Universidade de Trás-os-Montes e Alto Douro, Vila Real, p. 81.

LU, H., BUONGIORNO, J., 1993. Long- and short-term effects of alternative cutting regimes on economic returns and ecological diversity in mixed-species forests. *For. Ecol. Manage.* **58**: 173-192.

LUCAS, O.W.R., 1991. *The design of forest landscapes*. Oxford University Press. Oxford, p. 381.

LUÍS, J.S., 1997. *Ecologia, Silvicultura e Produção de povoamentos mistos*. Série Técnica-Científica da UTAD, 26. Vila Real, p. 74.

LUÍS, J.F.S., MONTEIRO, M.L., 1998. Dynamics of a broadleaved (*Castanea sativa*) conifer (*Pseudotsuga menziesii*) mixed stands in Northern Portugal. *For. Ecol. Manage.* **107**: 83-190.

MA, 2005. *Ecosystems and Human well-being: Biodiversity Synthesis*. Millennium Ecosystem Assessment. World Resources Institute, Washington, DC.

MACPHERSON, D.M., LIEFFERS, V.J., BLENIS, P.V., 2001. Productivity of aspen stands with and without a spruce understory in Alberta's boreal mixedwood forests. *For. Chron.* **77**: 351-356.

MAIA, M.L.M., 1988. *A Silvicultura do Castanheiro na Região de Trás-os-Montes - Resultados Preliminares*. INIA/EFN, Bragança, p. 241.

MALCOLM, D.C., MASON, W.L., 1999. *Experimental mixtures of Scots pine and birch: 30 year effects on production, vegetation and soils*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., Franc, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 79-87.

MASON. W.L., ALÍA, R., 2000. Current and future status of Scots pine (*Pinus sylvestris* L.) forests in Europe. *Investigación Agraria: Sistemas y Recursos Florestales* **1**: 317-335 (special issue).

MCPFE, UNECE, FAO, 2007. *State of Europe's Forests 2007*. MCPFE, Warsaw.

MENDES, A., 2011. *Equações de biomassa para Pinus pinaster e Quercus pyrenaica na região norte de Portugal*. Master Thesis. Universidade de Trás-os-Montes e Alto Douro, Vila Real, p. 84.

MONTAGNINI, F., 2000. Accumulation in above-ground biomass and soil storage of mineral nutrients in pure and mixed plantations in a humid tropical lowland. *For. Ecol. Manage.* **134**: 257-270. doi: 10.1016/S0378-1127(99)00262-5.

MONTEIRO ALVES, A.A., 1988. *Técnicas de Produção Florestal*. Instituto Nacional de Investigação Científica, 2ª Ed., Lisboa, p. 331.

MONTEIRO, M.L., 1991. *As Folhosas na Valorização da Propriedade rústica,* in: Seminário sobre Recursos Naturais do Nordeste Transmontano. ESAB / IPB. Bragança, p. 10.

MONTEIRO, M.L., LUÍS, J.S., JORDÃO, M.F., SARAIVA, D.A., 1994. *Eleven years results in a Castanea sativa and Pseudotsuga menziesii mixed stand in Northern Portugal*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, pp. 199-206.

MONTEIRO, M.L., CALDAS, S., PATRÍCIO, M.S., NUNES, L.F., PEREIRA, E., 2009. Mixed forests plantations with naturalized broadleaves and nitrogen fixing species, in: *XIII World Forestry Congress*. Buenos Aires.

MORGAN, J.L, CAMPBELL, J.M., MALCOLM, D.C., 1992. *Nitrogen relations of mixed-species stands on oligotrophic soils*, in: CANNELL, M.G.R., MALCOLM, D.C., ROBERTSON, P.A. (Eds.), The Ecology of Mixed-Species Stands of Trees. Blackwell, London, pp. 65-85.

NOBEL, P.S., FORSETH, I.N., LONG, S.P., 1993. *Canopy structure and light interception*, in: HALL, D.O., SCURLOCK, J.M.O., BOLHAÁR- NORDENKAMPF, H.R., LEEGOOD, R.C., LONG, S.P. (Eds.), Photosynthesis and Production in a Changing Environment: A Field and Laboratory Manual. Chapman & Hall, London, pp. 79-90.

NUNES, L., COUTINHO, J., NUNES, L.F., REGO, F.C., LOPES, D., 2011. Growth, soil properties and foliage chemical analysis comparison between pure and mixed stands of *Castanea sativa* Mill. and *Pseudotsuga menziesii* (Mirb.) Franco, in Northern Portugal. *For. Syst.* **20**(3): 496-507. doi: 10.5424/fs/20112003-11104.

NUNES, L., LOPES, D., REGO, F.C., GOWER, S.T., 2013. Aboveground biomass and net primary production of pine, oak and mixed pine-oak forests in the Vila Real district, Portugal. *For. Ecol. Manage*. **305**: 38-47.

NUNES, L., GOWER, S.T., MONTEIRO, M.L., LOPES, D., REGO, F.C., 2014. Growth dynamics and productivity of pure and mixed *Castanea sativa* Mill. and *Pseudotsuga menziesii* (Mirb.) Franco plantations in the north of Portugal. *Forest* **7**: 92-102.

OLIVER, C., LARSON, B.C., 1990. *Forest Stand Dynamics*. McGraw Hill. Biological Resource Management Series. New York, p. 467.

OLSTHOORN, A.F.M., HEKHUIS, H.J. (Eds.), 1995. *Management of mixed-species forest: silviculture and economics*. Proceedings of the first workshop, March 19-22, 1995, Wageningen, The Netherlands. Internal report DLO Institute for Forestry and Nature Research, Wageningen, p. 65.

OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J., PRETZSCH, H., HEKHUIS, H.J., FRANC, A. (Eds.), 1999. *Management of Mixed-Species Forest: Silviculture and Economics*. IBN Scientific Contributions 15, IBN-DLO Institute for Forestry and Nature Research, Wageningen, p. 389.

PATRÍCIO, M.S., NUNES, L.F., MONTEIRO, M.L., LOPES, D.M., 2010. Contributo da *Robinia pseudoacacia* para a Valorização de Espécies Folhosas Produtoras de Madeira de Qualidade: Um Caso de Estudo. *Silva Lusitana* (Número Especial): Florestas Mistas pp. 1-11.

PEREIRA, E., CALDAS, S., PATRÍCIO, M.S., NUNES, L., MONTEIRO, M.L., 2008. Mineralização do N do solo: caso de estudo num ensaio de plantações mistas de *Fraxinus excelsior* x *Alnus cordata*, in: *III Congresso Ibérico da Ciência do Solo*. Évora.

PEREIRA, E.L., SANTOS S.A.P., ARROBAS, M., PATRÍCIO, M.S., 2011. Microbial biomass and N mineralization in mixed plantations of broadleaves and nitrogen-fixing species. *For. Syst.* **20**(3): 516-524.

PEREIRA, L., LOURO, V., ROSÁRIO, L., ALMEIDA, A., 2006. *Desertification, territory and people, a holistic approach in the Portuguese context,* in: KEPNER, W.G., RUBIO, J.L., MOUAT, D.A., PEDRAZZINI, F. (Eds.), Desertification in the Mediterranean Region: a Security Issue. Nato Security through Science Series C, Springer, pp. 269-289.

PINTO da COSTA, M.E., 1992. *Metodologias de Análise da Estrutura de Povoamentos Mistos: Instalação, Recolha e Análise de Dados de Parcelas Permanentes na Serra da Lousã*. Doctoral Thesis. Universidade Técnica de Lisboa, Instituto Superior de Agronomia, Lisboa, p. 297.

PINTO da COSTA, M. E., PREUHSLER, T., 1994. *Excursion to the research plots in Lousã*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, Appendix 2.

PRETZSCH, H., BLOCK, J., DIELER, J., DONG, P.H., KOHNLE, U., NAGEL, J., SPELLMANN, H., ZINGG, A., 2010. Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. *Ann. For. Sci.* **67**: 712 p12. doi: 10.1051/forest/2010037.

RACKHAM, O., 1992. *Mixtures, mosaics and clones: the distribution of trees within European woods and forests*, in: CANNELL, M.G.R., MALCOLM, D.C., ROBERTSON, P.A. (Eds.), The Ecology of Mixed-Species Stands of Trees. Blackwell, London, pp. 1-20.

REGO, F.C., MONTEIRO, M.L., GERALDES, A., MESQUITA, J., 2011. Silvicultura de Povoamentos Mistos de *Quercus pyrenaica* e *Qurercus rotundifolia*: O Caso da Tapada da Nogueira. *Silva Lusitana* **19**(2): 135-148.

RESH, S.C., BINKLEY, D., PARROTTA, J.A., 2002. Greater soil carbon sequestration under nitrogen-fixing trees compared with Eucalyptus species. *Ecosystems* **5**: 217-231. doi: 10.1007/s10021-001-0067-3.

RICHARDS, A.E., FORRESTER, D.I., BAUHUS, J., SCHERER-LORENZEN, M., 2010. The influence of mixed tree plantations on the nutrition of individual species: a review. *Tree Physiol*. **30**: 1192-1208.

ROSÁRIO, L., 2004. *Indicadores de Desertificação para Portugal Continental*. Direcção Geral dos Recursos Florestais, Lisboa.

ROTHE, A., BINKLEY, D., 2001. Nutritional interactions in mixed species forests: a synthesis. *Can. J. For. Res.* **31**: 1855-1870.

ROXO, R., BENTO, J., 2010. *New mixed stands as a result of agricultural abandonment*, in: LOPES, D., TOMÉ, M., LIBERATO, M., SOARES, P. (Eds.), IUFRO conference Mixed and Pure Forests in a Changing World, Vila Real, Portugal, p. *Abst* 130.

SARAIVA, A.D., 1993. D*efinição das Árvores de Fruto em Castanea sativa Mill. num Ensaio de Consociação com Pseudotsuga.* Rel. Fim Curso. Prod. Agric. IPB. ESA. Bragança, p. 31.

SCHERER-LORENZEN, M., KÖRNER, C., SCHULZE, E.-D., 2005. *Forest diversity and function. Ecological Studies* 176, Springer, Berlin, Heidelberg, p. 399.

SEQUEIRA, N.M., CARVALHO OLIVEIRA, A., 1994. *Mixed stands in the forest of Mezio*, in: PINTO da COSTA, M.E., PREUHSLER, T. (Eds.), Mixed Stands, Research plots, Measurement and Results, Models. Proceedings from Symposium of the IUFRO Working groups S4.01-03 and S4.01-04. Lousã, Portugal, pp. 1-14.

SKOVSGAARD, J.P., EMBORG, J., 1999. *First attempts to establish a scientific basis for the silviculture of mixed stands in Denmark*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., Franc, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 95-101.

SMITH, D.M., 1986. *The Practice of Silviculture*. Eighth Edition. John Wiley & Sons, New York, p. 527.

SMITH, D.M., 1992. *Ideas about mixed stands*, in: KELTY, M.J., LARSON, B.C., OLIVER, C.D. (Eds.), The ecology and silviculture of mixed- species forests. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 281-287.

SU, Q., MACLEAN, D.A., NEEDHAM, T.D., 1996. The influence of hardwood content on balsam fir defoliation by spruce budworm. *Can. J. For. Res.* **26**: 1620-1628.

TOMÉ, M., LUÍS, J.S., MONTEIRO, M.L., OLIVEIRA, A.C., 1999. *Mixed-Species Forests in Portugal: perspectives for the development of management-oriented growth models*, in: OLSTHOORN, A.F.M., BARTELINK, H.H., GARDINER, J.J., PRETZSCH, H., HEKHUIS, H.J., Franc, A. (Eds.), Management of mixed-species forest: silviculture and economics. DLO Institute for Forestry and Nature Research (IBN-DLO), Wageningen, The Netherlands, pp. 175-185.

VANDERMEER, J., 1989. The ecology of intercropping. Cambridge University Press, Cambridge, p. 237.

WELKE, S.E., HOPE G.D., 2005. Influences of stand composition and age on forest floor processes and chemistry in pure and mixed stands of Douglas-fir and paper birch in interior British Columbia. *For. Ecol. Manage*. **219**: 29-42.

WEST, P.M., 2006. *Growing Plantation Forests*. Springer- Verlag Berlin Heidelberg, p. 304.

WIERMAN, C.A., OLIVER, C.D., 1979. Crown stratification by species in even-aged mixed stands of Douglas-fir-western hemlock. *Can. J. For. Res*. **9**: 1-9.

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Produção de Bioetanol com Base em Recursos da Floresta Portuguesa: Avaliação de Ciclo de Vida

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Sumário. O paradigma da eficiência energética e ambiental associada à produção de biocombustíveis é um tema central e primordial. A Avaliação de Ciclo de Vida é uma metodologia importante e reconhecida, utilizada neste estudo para avaliar as implicações ambientais da produção de etanol a partir da seguinte mistura de resíduos florestais: giesta (*Cytisus sp.*), carqueja (*Genista tridentata*), mimosa (*Acacia dealbata*), esteva (*Cistus ladanifer*), tojo (*Ulex europaeus*) e silva (*Rubus sp.*).

Os resultados mostram que utilizar este tipo de matérias-primas ajuda a reduzir o impacto ambiental da produção de etanol, com a manifesta redução das emissões de CO_2 na fase de crescimento das espécies (-10 700 kg de CO_2/tonelada de etanol produzida), contudo ainda há que tornar a unidade de produção, menos dependente do consumo de energias não-renováveis e, evidentemente, reduzir o ainda elevado impacto desta no ciclo de vida do etanol.
Palavras-chave: Impacto ambiental, resíduos florestais, biocombustíveis

Bioethanol production with resources of the Portuguese forest: life cycle assessment

Abstract. The paradigm of energy and environmental efficiency associated with production of biofuels is a central and essential theme. A Life Cycle Assessment is an important and recognized methodology. It is used in this study to assess the

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environmental impact of the production of ethanol from six forest residues: *Cytisus sp.*, *Genista tridentata*, *Acacia dealbata*, *Cistus ladanifer*, *Ulex europaeus* and plant *Rubus sp.*

The results clearly reveal that using this type of raw materials would help to reduce the environmental impact of ethanol production, due to the obvious reduction of CO_2 emissions during the growth stage (-10700 kg CO_2/ton of produced ethanol). However, further optimization would be needed in order to develop a more efficient biorefinery, less dependent on the consumption of non-renewable energy or even self-sufficient. This in turn would reduce the high impact level of the production of ethanol in the life cycle.
Key words: Environmental impact, forest residues, biofuels

Production de bioéthanol basé dans les ressources de la forêt portugaise: évaluation du cycle de vie

Résumé. Le paradigme de l'efficacité énergétique et l'environnant associé à la production de biocombustibles est un thème central et primordial. L'évaluation du cycle de vie est une méthode importante et reconnue, utilisé dans cette étude pour évaluer les incidences environnementales de la production d'éthanol à partir du mélange suivant de résidus forestiers: *Cytisus sp*, *Genista tridentata*, *Acacia dealbata*, *Cistus ladanifer*, *Ulex europaeus* et *Rubus sp*.

Les résultats révèlent que l'utilisation de ce type de matières premières contribue à réduire l'impact environnemental de la production d'éthanol, avec la réduction évidente des émissions de CO_2 durant la phase de croissance des espèces (-10 700 kg CO_2 /tonne de bioéthanol produit), mais encore faut-il rendre l'unité de fabrication, moins dépendante de la consommation d'énergie non renouvelable et naturellement réduire l'impact encore élevé dans le cycle de vie de l'éthanol.
Mots-clés: Impact environnemental, résidus forestiers, biocombustibles

Introdução

Vários países em todo o mundo, inclusive o Brasil, Estados Unidos, Canadá, Japão, Índia, China e até o continente Europeu, estão interessados em desenvolver o mercado dos biocombustíveis e estabelecer planos para o uso destes biocombustíveis. Tais interesses são motivados principalmente devido à atual dependência dos combustíveis fósseis e à necessidade de controlar as emissões de gases de efeito estufa (*greenhouse gases* - GHG) (MUSSATO *et al.*, 2010).

Os biocombustíveis líquidos, principalmente o bioetanol, fornecem uma das poucas opções para a substituição de combustíveis fósseis no curto e médio prazo, em motores de combustão interna por ciclo Otto, e são fortemente promovidos pela União Europeia (DIRETIVA 2003/30/EU, 2003; GONZÁLEZ-GARCÍA *et al.*, 2012b). O bioetanol tem atraído atenção especial devido à sua potencial utilização como combustível automóvel e as suas vantagens ambientais, energéticas e socioeconómicas em relação ao consumo de combustíveis fósseis e potencial de redução de GHG (GONZÁLEZ-GARCÍA *et al.*, 2010). A combustão do bioetanol, em vez de gasolina reduz a produção de chuvas ácidas causadas pelo dióxido de enxofre (MUSSATO *et al.*, 2010). Cerca de 95% do bioetanol atualmente produzido é de primeira geração, isto é, as matérias-primas são espécies agrícolas destinadas à alimentação humana e animal (HUANG *et al.*, 2009). Países como o Brasil e a Colômbia produzem-no a partir de cana-de-açúcar. Já noutras zonas do mundo, como os Estados Unidos, União Europeia e China, este é produzido a partir de milho. Em 2008, a produção total de bioetanol combustível em todo o mundo foi de $6.56 \cdot 10^{10}$ L (CHENG e TIMILSINA, 2011). O bioetanol também pode ser produzido a partir de materiais lenho-celulósicos, que é vulgarmente chamado bioetanol de segunda geração. As matérias-primas para o bioetanol de segunda geração incluem os resíduos agrícolas, resíduos de florestais e de processamento de madeiras, culturas energéticas e microalgas (CHENG e TIMILSINA, 2011). A segunda geração tem merecido especial atenção por parte da Agência Internacional de Energia (IEA, 2008).

Portugal é caracterizado por ter uma área muito significativa de matos e incultos (22%) e de povoamentos florestais puros e mistos de *Pinus pinaster* e *Eucalyptus globulus* (21%). Uma parte significativa do território (40-50%) é constituída por solos pobres, sem potencial para uso agrícola rentável (NUNES *et al.*, 2008; NUNES *et al.*, 2012; AMUTIO *et al.*, 2013). Em Portugal, não existem alternativas de uso sustentável para estes territórios nem nenhuma solução viável para rentabilizar o uso de recursos e resíduos destes territórios florestais. As matérias-primas provenientes de arbustos, terrenos baldios e resíduos agrícolas e florestais são as principais fontes para a produção de combustíveis líquidos renováveis e sustentáveis em Portugal, constituindo uma opção estratégica para a redução da dependência energética do sector dos transportes (AMUTIO *et al.*, 2013).

O impacto da substituição de combustíveis de transporte convencionais por biocombustíveis nas emissões de GHG é objeto de intenso debate e é importante para verificar o potencial perfil ambiental dos biocombustíveis, em comparação com o de combustíveis fósseis. Vários estudos de avaliações de ciclo de vida (*life cycle assessment* - LCA) vieram trazer diversas conclusões devido a diferenças na qualidade dos dados, nas condições de produção, no método usado para contabilizar os co-produtos e as hipóteses relativas a alterações nas características do solo, devido a mudanças no uso deste. Contudo, o bioetanol de segundo geração, produzido a partir de materiais lenho-celulósicos, foi considerado o biocombustível com maior potencial para substituir combustíveis fósseis e derivados com impactos ambientais menores do que o bioetanol de primeira geração convencional (DIAS *et al.*, 2012).

O objetivo desta investigação é a realização da avaliação de ciclo de vida do bioetanol de segunda geração, desde a recolha dos matos e incultos até à saída deste da unidade de produção.

Avaliação do ciclo de vida

Metodologia

Avaliação do ciclo de vida permite avaliar de forma global o impacto que tem o ciclo de vida de um produto sobre o meio ambiente (desde a recolha de matérias-primas até à produção, utilização, reciclagem e eliminação) (ISO 14044, 2006).

Objetivo, âmbito e unidade funcional

Neste estudo pretende-se analisar o impacto ambiental da produção de bioetanol a partir do seguinte conjunto de espécies florestais: giesta (*Cytisus sp.*), carqueja (*Genista tridentata*), mimosa (*Acacia dealbata*), esteva (*Cistus ladanifer*), tojo (*Ulex europaeus*) e silva (*Rubus sp.*) (Quadro 1). Para tal desenvolveu-se um modelo de ciclo de vida, para o qual quantificou-se as entradas e saídas do sistema de produção de bioetanol (Quadro 2) de acordo com os limites e condições estabelecidos na secção seguinte (Fronteiras do sistema), incluindo a matéria-prima, a energia, produtos químicos, emissões ambientais (resíduos sólidos e líquidos). Por sua vez, a cada entrada e saída do sistema de produção de etanol estão associadas entradas e saídas (energia e emissões ambientais) que foram também quantificadas e tidas em linha de conta.

Tendo em conta que a escolha da unidade funcional (*funcional unit* - FU) é dependente do objetivo do estudo, a FU escolhida foi a produção de 1 tonelada de bioetanol.

Fronteiras do sistema

Definiram-se as fronteiras e condições do sistema de modo a ser mais fácil compreender os resultados e comparar dados. Este foi dividido em dois subsistemas principais: a aquisição de matos e incultos (S1) e unidade de produção de bioetanol (S2). Na Figura 1 é apresentado um esquema global do sistema incluindo os principais processos, entradas e saídas de cada subsistema. A unidade de produção apresenta uma capacidade de processamento de 100 t/h de matéria-prima e tempo de operação de 8000 h/ano. O transporte e a gestão de resíduos (tratamento de águas residuais na ETAR, queima de resíduos sólidos e precipitados na câmara de combustão para geração de energia e aterro de precipitado da separação sólido-líquido e cinzas) foram incluídos dentro das fronteiras do sistema.

Quadro 1 *- Composição química em percentagem de matéria-prima seca (adaptado de DUARTE et al., 2013)*

	Giesta (*Cytisus sp.*)	**Carqueja (*Genista tridentata*)**	**Mimosa (*Acacia dealbata*)**	**Esteva (*Cistus ladanifer*)**	**Tojo (*Ulex europaeus*)**	**Silvas (*Rubus sp.*)**
Celulose	43,8	34,1	38,8	26,8	41,6	23,4
Hemicelulose	23,6	17,7	22,0	24,1	16,8	15,9
Açúcares totais	67,4	51,8	60,8	50,9	58,4	39,3
Lenhina	22,1	36,6	26,5	32,7	23,3	29,6
Cinzas	0,9	1,0	1,8	2,7	3,0	3,3
Extratáveis	1,7	5,7	5,2	9,4	6,4	11,0

Quadro 2 - Inventário do ciclo de vida do bioetanol desde a aquisição da matéria-prima (S1) à saída do bioetanol na unidade de produção (S2).[a] Químicos usados no pré-tratamento; [b] Nutrientes de maior volume de consumo usados na co-fermentação

Subsistemas		Materiais	Unidades	Valores
S1	Entradas:	**Transporte:**		
		Biomassa para unidade produção	ton/km	641,60
S2	Entradas:	**Matéria-prima:**		
		Matos e incultos (mistura verde)	ton	5,35
		Matos e incultos (mistura seca)	ton	3,40
		Químicos e Consumíveis:		
		Acetato de vinilo[a]	kg	1,50
		Ácido sulfúrico[a]	kg	75,03
		Carbonato/Hidróxido de cálcio[a]	kg	75,03
		Fosfato de diamónio[b]	kg	1,13
		Água de maceração de milho [b]	kg	8,77
		Enzimas	kg	348,00
		Nutrientes	kg	4,66
		Água	Não incluída	
		Energia:		
		Eletricidade	MWh	1,20
		Vapor	GJ	67,20
		Transporte:		
		Químicos e consumíveis	ton/km	205,65
		Resíduos (gesso e cinzas)	ton/km	51,60
	Saídas:	**Produto:**		
		Bioetanol	ton	1,00
		Resíduos para aterro:		
		Gesso	kg	241,67
		Cinzas	kg	80,83

Subsistema: Aquisição de matéria-prima (S1)

Este subsistema inclui as seguintes operações florestais e de pré-manuseamento da matéria-prima): corte, recolha e transporte. Este subsistema tem portanto em conta os consumos de combustível com as máquinas florestais no manuseamento e transporte da biomassa, bem como as emissões libertadas por estas. As operações florestais ocorrem em Oliveira do Hospital (região interior centro de Portugal), com uma produção de biomassa de 2 a 5 t/ha·ano (base seca), dependendo das espécies, e com um tempo de vida entre 3,5 a 4 anos (DUARTE *et al.*, 2013).

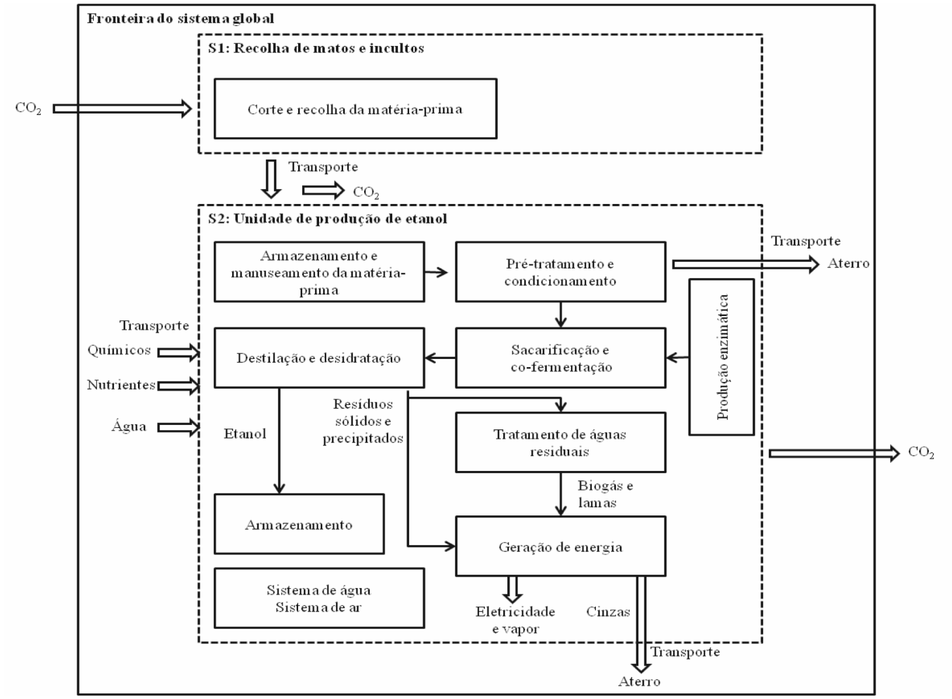

Figura 1 *- Fronteiras do sistema de produção de bioetanol. As linhas a tracejado (- - -) definem as fronteiras dos subsistemas (S1 e S2) e a linha continua (—) as fronteiras do sistema global (adaptado de GONZÁLEZ-GARCÍA et al., 2010)*

Subsistema: unidade de produção de bioetanol (S2)

Neste caso, o processo de conversão de bioetanol foi simulado e adaptado à composição dos matos e incultos selecionados (Quadro 1), tendo em conta os processos de produção escolhidos.

No processo de conversão, a celulose e hemicelulose são utilizadas para a produção de bioetanol. A fração de lenhina da biomassa, uma vez que tem um interessante valor calorífico, pode ser utilizada como combustível, bem como as lamas anaeróbicas e o biogás produzidos na unidade de tratamento de águas residuais. Foi modelada a sua utilização numa câmara de combustão a fim de produzir os requisitos de energia (calor e eletricidade) para diminuir as necessidades energéticas da planta. Este subsistema foi dividido em nove processos: manutenção e armazenagem de matérias-primas; pré-tratamento e condicionamento (onde biomassa é tratada com ácido sulfúrico diluído e vapor para libertar os açúcares hemi(celulósicos), lenhina e outros compostos); sacarificação (ou hidrólise enzimática, onde se recorre a celulases e hemicelulases que fracionam celulose e hemicelulose em açúcares simples como glucose e xilose) e co-fermentação (onde açúcares simples são utilizados por bactérias como *Zymomonas mobilis* ou leveduras como *Saccharomyces cerevisiae* capazes de produzir etanol) (MUSSATO *et al.*, 2010); destilação e desidratação (incluindo evaporação e separação sólido-líquido) para purificar e concentrar o bioetanol até 99,5%; o armazenamento de bioetanol; estação de tratamento de águas residuais (ETAR), onde o resíduo líquido que resta concluída a destilação e os condensados evaporados são tratados. A água tratada é reciclada para a refinaria; a geração de energia (elétrica e térmica do processo) a partir de resíduos sólidos provenientes da destilação, das lamas anaeróbicas e do biogás; a produção de enzimas e finalmente serviços auxiliares, que incluem a refrigeração e a esterilização de água e de ar comprimido. O precipitado da separação sólido-líquido e cinzas que resultam da produção de energia são enviadas para aterro.

Espécies lenho-celulósicas

As espécies de matos e incultos considerados neste estudo (Quadro 1) são considerados materiais lenho-celulósicos renováveis, abundantes em Portugal, sem utilização e com potencial para conversão em bioetanol (DUARTE *et al.*, 2013).

Inventário do ciclo de vida e software

Os dados do inventário estão resumidos no Quadro 2 para cada um dos subsistemas S1 e S2. O inventário do Subsistema S1 foi realizado com base no estudo (NUNES, 2008). As entradas e rendimentos do subsistema S2 obtiveram-se com base no estudo de GONZÁLEZ-GARCÍA *et al.*, (2012a). A distância de 60 km do transporte da biomassa para a unidade de produção foi efetuada por meio de veículos com uma capacidade de carga de 24 toneladas. O transporte de materiais de consumo foi realizado por camiões com uma capacidade 24 toneladas num raio de 200 km de distância. A distância entre a unidade de produção e o aterro é de 80 km também mediante camiões 24 t (NUNES, 2008). Para o transporte foi considerada a ida a cheio e o regresso a vazio. Com base nestes dados calcularam-se as entradas necessárias para produzir 1 tonelada de bioetanol.

O *software* utilizado na avaliação de impacto ambiental foi o *SimaPro 7.1.*, com o qual se caracterizaram 10 categorias de impacto (*impact categories* - IC) da metodologia *CML 2 baseline 2000*: potencial de diminuição abiótica (*abiotic resource depletion* - ADP), ou seja, potencial de esgotamento de recursos não-renováveis, potencial de acidificação (*acidification* - AP), potencial de eutrofização (*eutrophication* - EP), potencial de aquecimento global (*global warming* - GWP_{100}), potencial de destruição da camada de ozono (*ozone layer depletion* - ODP), potencial de toxicidade humana (*human toxicity* - HTP), potencial de ecotoxicidade aquática de água doce (*fresh water aquatic ecotoxicity* - FWAET), potencial de ecotoxicidade aquática marinha (*marine aquatic ecotoxicity* - MAET), potencial de ecotoxicidade terrestre (*terrestrial ecotoxicity* - TET) e o potencial de formação de oxidantes fotoquímicos (*photochemical oxidant formation* - POCP).

Os valores de cada categoria de impacto calcularam-se através da utilização de uma substância de referência (por exemplo, kg de CO_2 equivalente para as alterações climáticas). A contribuição de outras substâncias para a mesma categoria de impacto calculou-se através da conversão da quantidade dessas outras substâncias, equivalente da substância de referência (por exemplo, os efeitos de 1 ton de CH_4 são convertidos para a quantidade de CO_2 necessária para provocar o mesmo efeito num período de 100 anos).

Resultados e discussão

O perfil ambiental do ciclo de vida de produção de bioetanol de segunda geração, com base em recursos florestais na Região Centro de Portugal, é apresentado no Quadro 3. A avaliação deste ciclo de vida abrange o impacto ambiental (positivo e negativo) causado desde a recolha de matos e incultos (S1) até à saída da unidade de produção de bioetanol (S2) (Figura 1). As categorias com maior expressão no sistema (S1+S2) são por ordem decrescente: o MAET, GWP_{100}, HTP, FWAET e o ODP (em menor escala).

***Quadro 3** - Perfil ambiental do ciclo de vida do bioetanol*

Categoria de impacto	Unidade	Total	Biomassa	Químicos	Energia	Combustível
ADP	kg Sb eq	8,82	0	0,28	7,75	0,79
AP	kg SO_2 eq	21,80	0	1,40	19,10	1,33
EP	kg PO^{-3}_4 eq	2,42	0	0,01	2,12	0,29
GWP_{100}	kg CO_2 eq	-9320,00	-10700,00	94,03	1176,00	128,75
ODP	kg CFC-11 eq	$9{,}99 \cdot 10^{-4}$	0	$5{,}49 \cdot 10^{-6}$	$8{,}86 \cdot 10^{-4}$	$1{,}07 \cdot 10^{-4}$
HTP	kg 1,4-DB eq	748,00	0	12,71	711,00	24,38
FWAET	kg 1,4-DB eq	100,00	0	2,52	95,70	1,88
MAET	kg 1,4-DB eq	337000,00	0	7220,00	325400,00	4307,30
TET	kg 1,4-DB eq	7,53	0	0,06	7,45	0,03
POCP	kg C_2H_4 eq	2,20	0	0,06	2,11	0,03

Para uma melhor compreensão dos resultados do estudo de impacto, estes são apresentados segundo as entradas do sistema: biomassa, químicos, energia e combustível. Na Figura 2 encontram-se resumidos os potencias contributos, em termos de impacto, de cada entrada para cada uma das categorias de impacto selecionadas na produção de uma tonelada de bioetanol.

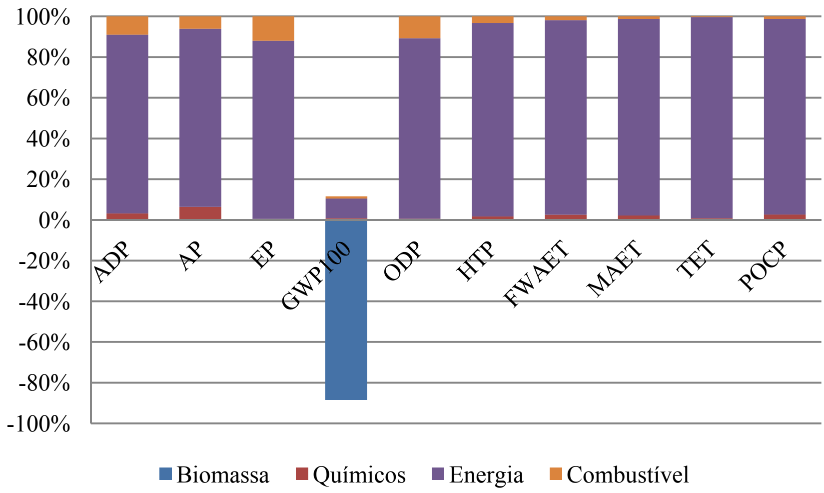

***Figura 2** - Impactos ambientais do sistema de produção de bioetanol divididos por entradas: biomassa, químicos, energia e combustível*

A energia (elétrica e térmica) é a entrada que apresenta maior contributo para todas as IC (entre 88 a 99%). A exceção é na categoria GWP_{100} (13%) onde a entrada que apresenta maior contributo é a biomassa (matos e incultos). Seguem-se as entradas de combustível e de químicos com uma contribuição para todas as IC entre 0,4 – 12% e 0,5 – 6%, respetivamente.

As entradas de energia, combustível e químicos, contribuem de forma negativa para o impacto ambiental, enquanto a biomassa dá um contributo positivo.

Potencial de aquecimento global, GWP_{100}

A mistura de giesta, carqueja, mimosa, esteva, tojo e silva revela ser uma opção interessante para a produção de bioetanol de segunda geração em Portugal. O facto de estas espécies regenerarem naturalmente, dispensa a necessidade de atividade agrícola e a aplicação de fertilizantes, pesticidas e herbicidas, contribuindo para um melhor desempenho. Portanto, não existe o contributo dos GHG produzidos devido à aplicação e produção de agroquímicos (MILÁ *et al.*, 2006; GONZÁLEZ-GARCÍA *et al.*, 2012a). Este contributo nulo para o impacto ambiental é notado em todas as categorias, expeto na GWP_{100}, em que a entrada desta biomassa dá um contributo positivo, que se explica pela captação do CO_2 da atmosfera durante o crescimento das espécies. A captação de CO_2 é de tal ordem (-10700 kg de CO_2) que compensa as emissões deste GHG produzido devido ao consumo das outras entradas noutras fases do sistema, como: na geração de energia elétrica e realização da destilação na unidade de produção (1176 kg de CO_2); na queima de combustível por parte de camiões de transporte (128,75 kg de CO_2); na fabricação de químicos que dão entrada sobretudo na fase de pré-tratamento (94 kg de CO_2). Posto isto, o contributo positivo da captação de CO_2 sobrepõe-se ao do emitido e traduz-se no valor negativo de CO_2 (-9320 kg de CO_2) que contribui positivamente para o GWP_{100}.

A utilização de matos e incultos como matéria-prima na produção de bioetanol permite ainda ajudar a combater outro problema ambiental, os incêndios florestais, que apresenta um impacto negativo em Portugal. Do conjunto de espécies consideradas, três (giesta, mimosa, tojo) encontram-se de forma significativa no território nacional português e apresentam mesmo níveis totais de açúcares acima dos verificados para algumas das espécies correntes mais estudadas como potenciais matérias-primas em unidades de produção de bioetanol, nomeadamente o eucalipto (*Eucalyptus globulus*) DUARTE *et al.*, 2013) e palha de trigo (*Triticum spp.*) (SÁNCHEZ *et al.*, 2009). Do ponto de vista económico, a elevada disponibilidade destas espécies em Portugal, o facto de não ostentarem aplicação comercial, aliado ao facto de não exigirem gastos com atividades agrícolas ou de silvicultura, nem com agroquímicos, torna este tipo de matéria-prima mais "amiga do ambiente" e mais económica do que algumas das matérias-primas já utilizadas na produção de bioetanol de segunda geração.

Potencial destruição da camada de ozono (ODP) e potencial de diminiuição abiótica (ADP)

As categorias OPD e ADP são mais afetadas pelas atividades que exigem consumo de energia (89% e 88%, respetivamente) e de combustível (11% e 9%, respetivamente), mais especificamente, que exigem a produção e combustão de fontes de energia não-renováveis (gás natural, diesel, etc.). Essas atividades são o pré-tratamento, a hidrólise, a produção de enzimas, a destilação, a desidratação e o transporte. Assim, estes resultados devem-se à necessidade deste tipo de fontes não-renováveis na produção dos produtos (como químicos, nutrientes, etc.) que são necessários nestas atividades. Já no transporte os valores obtidos devem-se à combustão de combustível no transporte de biomassa, de químicos e resíduos sólidos.

A produção de eletricidade na unidade de produção de bioetanol pouco atenua a contribuição para estas duas categorias, visto não existirem maiores níveis de produção de eletricidade capazes de substituir uma maior porção das fontes não-renováveis utilizadas.

Potencial acidificação (AP) e potencial eutrofização (EP)

À semelhança do que se verifica com as categorias OPD e ADP, as categorias AP e EP são mais afetadas pelas mesmas atividades, pelos mesmos motivos. Emissões de SO_2 que são emissões acidificantes provêm da produção e combustão de fontes de energia não-renováveis, enquanto emissões de NO_x, que são eutrofizantes, provêm maioritariamente da combustão deste tipo de fontes.

É de realçar que não existe um maior contributo para estas categorias, de emissões acidificantes e eutrofizantes, de NH_3 e PO^{-3}_4, respetivamente, pelo facto de não serem produzidos e aplicados agroquímicos.

Potencial de formação de oxidantes fotoquímicos (POCP)

Esta categoria de impacto é consideravelmente afetada (96%) pela difusão de emissões de acetaldeídos, que se formam em algumas das fases de produção de bioetanol de maior consumo de energia, como a produção de enzimas, geração de energia e a destilação. Esta categoria é ainda afetada (1%), pela emissão de foto-oxidantes, como o CO e compostos orgânicos voláteis com exceção do metano (*non-methane volatile organic compounds* - NMVOC) provenientes da queima de combustíveis fosseis em máquinas florestais e camiões de transporte. No entanto, há que realçar que existe menos um contributo a aumentar a expressão desta categoria, que é o contributo proveniente da aplicação de agroquímicos, sobretudos dos fertilizantes. Em outros estudos de LCA, esta categoria é consideravelmente afetada devido a emissões de SO_2 que surgem com a aplicação de fertilizantes à base fósforo (GONZÁLEZ-GARCÍA *et al.*, 2012a).

Potenciais de ecotoxicidade (HTP, FWAET, MAET, TET)

As categorias de ecotoxicidade: potencial de toxicidade humana (*human toxicity* - HTP); potencial de ecotoxicidade aquática de água doce (*fresh water aquatic ecotoxicity* - FWAET); potencial de ecotoxicidade aquática marinha (*marine aquatic ecotoxicity* - MAET); e potencial de ecotoxicidade terrestre (*terrestrial ecotoxicity* - TET) refletem o contributo toxicológico das etapas de produção de bioetanol (entre 95-99%).

As elevadas produções e emissões de compostos tóxicos para o Homem e o meio ambiente, como o SO_2 e CO, acontecem devido à produção e utilização de combustíveis fósseis em transportes e na produção de químicos, necessários sobretudo no: pré-tratamento, hidrólise, produção de enzimas, destilação, tratamento de água residuais (*waste water treatment* - WWT).

De entre as etapas, o contributo do pré-tratamento e da hidrólise deve-se à produção de ácido sulfúrico e compostos inorgânicos à base de cálcio (carbonato de cálcio ou hidróxido de cálcio) que são usados nestas; da produção de enzimas deve-se à produção de respetivos químicos necessários a esta; da destilação deve-se à produção e libertação acetaldeídos e do WWT deve-se à produção de NaOH que é usado neste. Estas mesmas etapas de produção de bioetanol são mencionadas pelos mesmos motivos, noutros casos de LCA em que é utilizada semelhante tecnologia e processos de produção, a partir de matérias-primas lenho-celulósicas, como a palha de trigo (WANG *et al.*, 2013) ou a palha de milho (LUO *et al.*, 2009).

Contudo, o maior impacto ambiental e até para o ser humano verifica-se na fase de produção de energia para a biorrefinaria. A queima de resíduos sólidos, biogás, lamas e até de alguns compostos químicos oriundos das etapas de produção de etanol, contribui com a produção de compostos tóxicos para os ecossistemas aquáticos e terrestes. De entre as categorias de ecotoxicidade, MAET apresenta os valores mais elevados por apresentar uma concentração prevista de substâncias tóxicas na água marinha superior à concentração prevista nos outros (água doce, terrestre, ser humano).

O maior contributo negativo para o impacto ambiental deve-se portanto às emissões de poluentes resultantes da: produção de combustíveis fósseis; consumo destes na unidade de produção de bioetanol; consumo destes nas unidades de fabricação dos químicos que são matéria-prima na unidade de produção de bioetanol; e queima de resíduos para produção de energia. Por outras palavras, o maior contributo negativo para o impacto ambiental deve-se à entrada de energias não-renováveis. A necessidade de recorrer a este tipo de fontes seria menor se a unidade funcional fosse capaz de colmatar as necessidades energéticas com a autogeração de energia e com a utilização de tecnologia (equipamentos/maquinaria) e condições de operação com níveis de consumo mais reduzidos. Neste sentido têm sido feitos esforços para desenvolver processos e tecnologias mais eficientes na deslenhificação, hidrólise e fermentação da biomassa e na separação e purificação do bioetanol (LUO *et al.*, 2009; BORRION *et al.*2012).

Uma solução para diminuir o contributo negativo da entrada de energia poderá passar por uma maior utilização de processos biológicos (no pré-tratamento e na fermentação com microrganismos), diminuindo assim a produção e uso de químicos. Desenvolvimentos em investigação experimental no campo da biotecnologia têm ocorrido com o sentido de:

- criar novos e mais eficazes sistemas enzimáticos aplicados na hidrólise da celulose;
- desenvolver microrganismos capazes de metabolizar pentoses e hexoses e, simultaneamente, resistir à inibição imposta pelos inibidores formados (sacarificação e co-fermentação simultânea);
- reduzir inibidores que afetam o rendimento de microrganismos capazes de metabolizar açúcares e

- determinar a forma de manter estável o desempenho de microrganismos geneticamente modificados em operações de fermentação em escala comercial (MUSSATO *et al.*, 2010).

Conclusões

A Avaliação de Ciclo de Vida realizada permite concluir que a mistura de matos e incultos revela ser uma opção interessante enquanto matéria-prima para a produção de bioetanol de segunda geração. Uma vez proveniente de regeneração natural, a matéria-prima não contribui para um impacto ambiental negativo durante o seu crescimento. Não exige o uso de agroquímicos nem de operações agrícolas para manutenção das culturas, que comummente contribuem, e de forma significativa, para as categorias de eutrofização e acidificação.

O ainda elevado contributo negativo associado ao consumo de energia na unidade de produção, poderá ser contornado com o desenvolvimento de tecnologias mais eficientes (na deslenhificação, hidrólise e fermentação da biomassa e na destilação do bioetanol), que exijam menor consumo de energia e que ajudem a tornar a unidade de produção autossustentável quanto à produção de energia elétrica. Outra hipótese será apostar no melhoramento das enzimas e do processo de sacarificação e co-fermentação simultânea.

Referências bibliográficas

ADEN, A., RUTH, M., IBSEN, K., JECHURA, J., NEEVES, K., SHEENHAN, J., 2002. *Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover*. Golden, CO: National Renewable Energy Laboratory; NREL/TP-510-32438, 154 pp.

AMUTIO, M., LOPEZ, G., ALVAREZ, J., MOREIRA, R., DUARTE, G., NUNES, J., OLAZARA, M., BILBAO, J., 2013. Flash pyrolysis of forestry residues from the Portuguese Central Inland Region within the framework of the BioREFINA-Ter project. *Bioresource Technology* **150**: 412-419.

BORRION, A.L., MCMANUS, M.C., HAMMOND, G.P., 2012. Environmental life cycle assessment of lignocellulosic conversion to ethanol: A review. *Renewable and Sustainable Energy Reviews* **16**: 4638-4650.

CHENG, J.J., TIMILSINA, G.R., 2011. Status and barriers of advanced biofuel technologies: A review. *Renewable Energy* **36**: 3541-3549.

DIAS, M.O.S., JUNQUEIRA, T.L., CAVALETT, O., CUNHA, M.P., JESUS, C.D.F.,. ROSSELL, C.E.V., FILHO, R.M., BONOMI, A., 2012. Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. *Bioresource Technology* **103**: 152-161.

DIRETIVA 2003/30/EC. EU DIRECTIVE 2003/30/EC of the European Parliament and of the Council of May 8, 2003 on the promotion of the use of biofuels or other renewable fuels for transport. http://ec.europa.eu/energy/res/legislation/doc/biofuels/en_final.pdf2003. [acedido a 01.09.2010].

DUARTE, G.V., MOURA, A.I., MOREIRA, R., NUNES, J., FIGUEIREDO, M.M., CARVALHO, M.G., 2013. Evaluation of Several Forest Residues as Potential Raw Material for Bioethanol Production in Portugal. *Journal of Bioprocess Engineering and Biorefinery* **2**: 1-6.

GONZÁLEZ-GARCÍA, S., MOREIRA, M.T., FEIJOO, G., 2010. Comparative environmental performance of lignocellulosic etanol from different feedstocks. *Renewable and Sustainable Energy Reviews* **14**: 2077-2085.

GONZÁLEZ-GARCÍA, S., MOREIRA, M.T., FEIJOO, G., MURPHY, R.J., 2012a. Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar). *Biomass and bioenergy* **39**: 378-388.

GONZÁLEZ-GARCÍA, S., MOREIRA, M.T., FEIJOO, G., 2012b. Environmental aspects of eucalyptus based ethanol production and use. *Science of the Total Environment* **438**: 1-8.

HUANG, H., RAMASWAMY, S., AL-DAJANI, W., TSCHIRNER, U., CAIRNCROSS, R.A., 2009. Effect of biomass species and plant size on cellulosic ethanol: A comparative process and economic analysis. *Biomass and bioenergy* **33**: 234-246.

IEA (INTERNATIONAL ENERGY AGENCY), 2008. From 1st to 2nd generation biofuel technologies. An overview of current industry and RD&D activities. Report. 16 pp..

ISO 14044, 2006. *Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization, Geneva, Switzerland.

LUO, L., VOET, E., HUPPES, G., 2009. An energy analysis of ethanol from cellulosic feedstock–Corn stover. *Renewable and Sustainable Energy Reviews* **13**: 2003-2011.

MILA'I CANALS, L., BURNIP, G.M., COWELL, S.J., 2006. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. *Agriculture, Ecosystems and Environment* **114**: 226-238.

MUSSATO, I.S., DRAGONE, G., GUIMARÃES, P.M.R., SILVA, J.P.A., CARNEIRO, L.M., ROBERTO, I.C., VICENTE, A., DOMINGUES, L., TEIXEIRA, J.A., 2010. Technological trends, global market, and challenges of bio-ethanol production. *Biotechnology Advances*. **28**: 817-830.

NUNES, J., 2008. *Avaliação integrada da produção de eletricidade com base em biomassa lenho-celulósica em Portugal: Emissões de GEE, análise tecnológica e energética de ciclo de vida.* Tese de metrado. Portugal, Coimbra, Universidade de Coimbra – Faculdade de Ciências e Tecnologia.

NUNES, J., FIERRO, J., AND FREITAS, H., 2012. Sustainable management of forest ecosystems and lignocellulosic biomass use: A case study from Portugal. *20th European Biomass Conference and Exhibition*, June, Milan, Italy.

SÁNCHEZ, C., 2009. Lignocellulosic residues: Biodegradation and bioconversion by fungi. *Biotechnology Advances* **27**: 185-194.

WANG, L., LITTLEWOOD, J., MURPHY, R.J., 2013. Environmental sustainability of bioethanol production from wheat straw in the UK. *Renewable and Sustainable Energy Reviews* **28**: 715-725.

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Cost Analysis of Short Rotation Coppice with Poplar in Portugal for the Production of Biomass and Chemicals

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Abstract. In this study an evaluation of the potential economic feasibility of woody poplar short rotation coppices (SRCs) in Southern Portugal was done on a hectare unit area basis. The assessment was based on the financial analysis of an investment on a poplar SRC production system, with a spreadsheet model (POPFINUA) adapted to water and nutrient needs by the plantation, to be supplied through irrigation, fertilization and application of superabsorbent polymers for water storage and releasing in soil. The estimated period for lifecycle of the cultivation was 15 years, under a three year rotation, with a cost structure wherein maintenance, establishment, general and harvesting costs accounted to 9%, 18%, 29% and 44% of the total costs, respectively. The predicted value of costs per energy unit at the end of plantation lifetimes, was 2.8€ GJ^{-1}, above the threshold of the average delivered cost of coal, i.e., 1.2€ GJ^{-1}. A sensitivity analysis of economic feasibility was done based on several key variables namely biomass yield, land rent costs, discount rate, biomass price and establishment grants and annual incentives. This analysis showed that biomass yield was the variable with higher impact on the economic results.
Key words: Biomass, poplar, short rotation coppice, economic feasibility, lifecycle, sensitivity analysis

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Uma análise de custos da talhadia lenhosa de curta duração de choupo em Portugal para a produção de biomassa e produtos químicos

Sumário. Neste estudo foi efetuada uma avaliação do potencial económico por unidade de área (ha.) do cultivo de talhadias de choupo de curta rotação (SRC) no Sul de Portugal. Os cálculos foram realizados com um modelo em folha de cálculo, POPFINUA, adaptado para a satisfação das necessidades de água e nutrientes da plantação, através das operações de rega, fertilização e aplicação de polímeros superabsorvente no solo para retenção e libertação de água. O período estimado para o ciclo de vida da plantação foi de 15 anos, com períodos de rotação entre cortes de 3 anos, com uma estrutura de custos em que a manutenção, instalação, operações gerais e corte correspondem respetivamente a 9%, 18%, 29% e 44% dos custos totais. Os valores previstos dos custos por unidade de energia no termo do ciclo de vida das plantações foram 2,8€ GJ^{-1}, acima do limiar padrão do custo de carvão que é de 1,2€ GJ^{-1}. Foi realizada uma análise de sensibilidade da viabilidade económica da cultura, com base na variação de variáveis fundamentais como o rendimento em biomassa, os custos do aluguer do terreno, a taxa de juro, o preço da biomassa, incentivos à instalação da cultura e subsídios anuais. Esta análise evidenciou que o rendimento em biomassa foi a variável com maior impacto nos resultados económicos.

Palavras-chave: Biomassa, choupo, talhadia de curta rotação, viabilidade económica, ciclo de vida, análise de sensibilidade

Une analyse des coûts de taillis à courte rotation des peupliers au Portugal pour la production de biomasse et les produits chimiques

Résumé: Dans cette étude une évaluation a été réalisée du potentiel économique par unité de surface (ha) de la culture de taillis à courte rotation peupliers (TCR) dans le sud du Portugal. Les calculs ont été effectués avec un modèle de feuille de calcul, POPFINUA, adapté aux besoins de l'eau et des éléments nutritifs de la plantation, à travers les opérations d'arrosage, fertilisation et applications de polymères super absorbants sur le sol pour rétention et libération de l'eau. La période estimée pour le cycle de vie de la plantation était de 15 ans, avec des périodes de rotation entre les coupes de 3 ans, et une structure de coûts qui compris l'entretien, installation, opérations générales et coupe, correspondent respectivement à 9%, 18%, 29% et 44% du total des coûts. Les valeurs prédites du coût par unité d'énergie à la fin du cycle de vie des cultures étaient 2.8€ GJ^{-1}, supérieur au coût de seuil standard de charbon de 1.2€ GJ^{-1}. Une analyse de sensibilité de la viabilité économique de la culture a été réalisée, basée sur la variation des variables fondamentales, telles que le rendement en biomasse, coûts de location des terrains, le taux d'intérêt, le prix de la biomasse, incitations pour l'installation de la culture et des subventions annuelles. Cette analyse a montré que le rendement en biomasse était la variable avec le plus d'impact sur les performances économiques.

Mots-clés: Biomasse, peuplier, taillis à courte rotation, faisabilité économique, cycle de vie, analyse de sensibilité

Introduction

World energy consumption is expected to grow by about 56% between 2010 and 2014 (INTERNATIONAL ENERGY OUTLOOK, 2014). To reduce the dependency of fossil fuels and to mitigate climate change, the European Union has developed a policy aiming to increase the share of renewable energy to 20% of the total energy consumption by the year 2020. (e.g., DI MATTEO *et al.*, 2012; KASMIOU and CEULEMANS, 2013). Biomass is one of the most suitable renewable energy sources for energy and chemicals, and its main advantages are local availability, CO_2-neutral character and also unique aptitude on replacing fossil fuels in solid, liquid and gaseous forms. Currently about 0.19% of the world total land area and about 0.5 - 1.7% of the global agricultural land are used to grow biomass fuels (LADANAI and VINTERBÄCK, 2009). This tendency occurs also in Europe (HAUK *et al.*, 2014). Short rotation coppices (SRCs), such as poplar, willow or eucalypt cultivations, are one promising sources of bioenergy, expected to play a major role in the biomass supply (GASOL *et al.*, 2009; BLANCO *et al.*, 2010). They are able to reduce greenhouse gas emissions by about 90% in comparison to the fossil energy baseline (DJOMO *et al.*, 2011). SRCs are characterized by short cycles of two to five years and planting densities of 3 000–10 000 plants per hectare. SRC plantations can be viable for periods of 15 to 30 years, depending on the productivity of the stools, before replanting becomes necessary. Poplar (*Populus*), is one of the main species used in Europe for SRC cultivations, fitting well the requirements of SRCs (*e.g.*, BLANCO *et al.*, 2010; DILLEN *et al.*, 2010). Indeed this species shows a high plasticity to different latitudes and environments, high stool growing rates, high potential for genetic improvement (PARIS *et al.*, 2011) adaptability to summer water stress and minimum requirement of herbicides and fertilizers (e.g., BLANCO *et al.*, 2010; DI MATTEO *et al.*, 2012; MARTINEZ, 2012a). To bring the SRCs concept to a commercial scale with economic viability, efforts have been made to maximize the mechanization of the culture: mechanical planting, weed control, nutrient and herbicide applications, irrigation and harvesting. The dominant approach was to adapt the agriculture techniques to SRCs. Environmental gains, in terms of biodiversity or soil fertility, are also achieved (e.g., KAHLE *et al.*, 2007). An appraisal of the global SRC productive cycle can be found in references such as BLANCO *et al.*, 2010, BERHONGARAY *et al.*, 2013, RODRIGUES *et al.*, 2015 or PEREIRA *et al.*, 2016.

Biomass yield is a fundamental variable influencing the financial feasibility of the SRC cultivation. In Portugal, biomass yield is favored by solar radiation but restrained by low rainfall in summer (e.g., RODRIGUES *et al*., 2011; PITA *et al.*, 2013). Dry matter yields in the range of 10 – 35 Mg ha^{-1} yr^{-1} for poplar and eucalypt intensive management coppices aimed to bioenergy and pulp production can be estimated for poplar and eucalypt intensive management coppices in Portugal (e.g., GONÇALVES, 2010; RODRIGUES *et al*., 2011; MARTINEZ, 2012b). This allows inferring that a value for minimum dry matter yield of 12 Mg ha^{-1} $year^{-1}$, required to guarantee the break-even point, is credible. Portuguese forest area covers about 35% of the territory, with the potential area for SRCs being about 1.5 Mha of shrub or uncultivated lands (ICNF, 2013). Other European countries show a similar potential for this kind of cultivation. For example, in Germany at least 680000 ha could suitable for SRCs (SCHWEIER and BECKER, 2013) from which only about 5000 ha are actually cultivated.

A positive financial balance is of course a precondition for the expansion of SRCs. A general conclusion, pointed by the literature, is that SRCs (*e.g.*, PARIS *et al*., 2011; KASMIOUI and CEULEMANS, 2012; SCHWEIER and BECKER, 2013) are not financially viable without government incentives. So, most studies focus on the need for active support mechanisms, such as establishment grants and logistical support for a regulated market with incentives under the European Common Agricultural Policy. At the national level, the government incentives vary significantly with some countries providing no incentives, while others like Italy provide establishment grants varying between 1600€/ha-5000€/ha to plantation and 100-100€/ha - 500€/ha y^{-1} for annual cultivation (*e.g*., KASMIOUI and CEULEMANS, 2012). A comprehensive study (KASMIOUI and CEULEMANS, 2012) making a comparative analysis of the financial feasibility of 23 SRC case studies relative to several countries (18 European) is very elucidative about the cost variability. Indeed, according to this study, the production costs of SRCs, expressed in Euros per GJ of bioenergy, ranged from 0.8€ GJ^{-1} to 5€ GJ^{-1}, usually higher than the delivered cost of coal at plant gate (on average 1.2€ GJ^{-1}). According to this analysis, establishment and harvest costs accounted to about 60% of the total cultivation costs. The cases of Sweden and Denmark with scale economies for use planting and harvesting equipment are peculiar in the sense that these operations account to just circa 38% of the total costs. The evidences available (e.g., KASMIOUI and CEULEMANS, 2012; HAUK *et al.,* 2014) showed also the difficulty to compare different SRCs systems due to non-uniform criteria of cost evaluation. Another study, (KASMIOUI and CEULEMANS, 2013), representative of temperate zones without irrigation, indicates a cost structure of SRC cultivation including general costs (land rent and overheads) establishment, (site preparation and planting) maintenance (weed control) and biomass harvesting costs corresponding to average values of 37%, 16%, 2% and 45-50%, respectively. Also data reported by Hauk et al., 2014, representative of costs of SRC cultivations representative of temperate areas showed that the three main cost units are land rent and harvesting and chipping, each representing an average 34% of total costs with plant establishment representing 25% of the total costs.

This study aimed to do a prospective analysis of the financial feasibility of one possible poplar SRCs case study, in Elvas, southern Portugal, using the tested spreadsheet model POPFINUA, developed for detailed analysis of the profitability of poplar SRCs in Lochristi, Belgium (KASMIOU and CEULEMANS, 2013). This spreadsheet model was adapted to accommodate differences at Elvas, comparatively to Belgium, due to Mediterranean climate and soil conditions, where the inclusion of fertilization and drip irrigation was complemented with superabsorbent polymer application.

The fertilization considered as adequate for poplar cultivations should assure that soils concentrations of assimilable nitrogen, phosphorus and potassium are 50, 30 and 100 ppm, respectively (*e.g.*, BLANCO *et al.*, 2010; BLANCO, 2012). Annual requirements recommended in soil for poplar SRC cultivation are 150-200 kg N ha^{-1}, 120 kg P ha^{-1} and 250 kg K ha^{-1} (MARTINEZ, 2012a; MARTINEZ, 2012b). In Italy, the good practices point to amounts of fertilization of phosphorus (P_2O_5) and potassium (K_2O) of 100 kg ha^{-1} each (*e.g.*, DI MATTEO *et al.*, 2012).

In Mediterranean areas, where poplar SRCs crops are prone to seasonal drought, irrigation is necessary to guarantee an adequate hydrous status of plants and thereby adequate crop yield. Water scarcity induces a debilitating effect on plants also turning them more susceptible to pests. The irrigation should keep soil water content at the soil field capacity say, between 9% in sandy soils and 35% in loamy soils. The minimum rainfall for poplar SRC should be 500 mm, preferably with an even seasonal distribution (BLANCO, 2012; MARTINEZ, 2012a) Data obtained in Spain for maximum daily water consumption for poplar two year coppices are in the range of 20 m^3-50 m^3 per hectare (*e.g.*, MARTINEZ, 2012a). An irrigation of 350 m^3 ha^{-1} $month^{-1}$ in summer is indicated as guideline for good management practices of poplar SRC (DI MATTEO *et al.*, 2012). Drip irrigation is the recommended option to poplar SRCs, due to advantages related to higher water savings, process automation, possible ferti-irrigation, evapotranspiration reduction or minimizing of weed proliferation (*e.g.*, BLANCO *et al.*, 2010; OTERO and ARRIETA, 2012).

The application of superabsorbent polymers (SAPs) (*e.g.*, sodium polimetacrylate) with high water retention and desorption (CASQUILHO *et al.*, 2013) (*e.g.*, 1g SAP retains 300g to 500g), forming a hydrogel, at half distance between rows and a 30cm depth, is a way of relinquishing available water to plants by successive cycles of shrinking-swelling. The SAP water capacity lasts for a period up to nine years. In agriculture applications SAP utilization, by establishing a water gradient in the soil, should encourage the development of deep root systems, allowing plants to optimize search for nutrients and water. This improves plant growth, decreases the plant death rate and reduces irrigation needs (e.g., RAJU and RAJU, 2001; HÜTERMANN *et al.*, 2009; CASQUILHO *et al.*, 2013).

Within the context of the potential of poplar SRCs as a bioenergy source this study, based on operational and market data, intended (i): evaluate for the cost structure and financial lifecycle, for unit area, of a poplar SRC cultivation submitted to fertilization, irrigation and superabsorbent polymer application in an Mediterranean area in Portugal and (ii) to make a sensitivity analysis of SRCs economic feasibility under variation of relevant factors such as biomass yield, land rent costs, discount rate, establishment and annual subsidies and biomass price.

Materials and methods

Site characteristics

As a case study for the Mediterranean region a poplar SRC 15 hect. site to be installed in 2017 in Elvas (Southern Portugal-38º54'53''N, 7º19'11W) was chosen. For this site, the data information used were obtained from the technical and scientific literature on SRCs and from direct consultations in the market of goods and services needed to the implementation of the cultivation. The site will be located at an altitude of 184 m above sea level, flat topography, sandy soil with poor natural drainage, average annual temperature of 16.9ºC and average annual precipitation of 489 mm.

The planned poplar plantation density should be 6700 plants hec.$^{-1}$ submitted to a harvesting operation every three years. After ploughing of the soil and application of chemical herbicides (glycophosate, Fluroxypyr and Clopyralid), 25 cm unrooted stem cuttings were planted under a one row scheme with a 3 m distance between rows and a 0.5 m between plants in a row. Expected standard conditions were: biomass increment was 4 Mg ha^{-1} $year^{-1}$ in the first three year period and 12 Mg ha^{-1} $year^{-1}$ in the remaining years of the productive lifecycle; harvesting in every three year periods; land rental of 180€ ha^{-1} $year^{-1}$, the yearly discount rate of 4%; diesel price of 1€ l^{-1}; biomass sales price at 50% moisture content of 40€ Mg^{-1}, and labour costs of 10€ h^{-1} for agricultural labourer and 12€ h^{-1} for agricultural manager. The yield of the first harvesting is lower than onwards, due to the need of plant for diverting photosynthetic energy to the development of a mature root system to enable for an adequate water and nutrient supply. Also the small plant cuttings must initially compete fiercely with weeds for light, nutrients and water.

The prevalent empirical criteria for land rental cost estimation was 180€ ha^{-1} $year^{-1}$ of was market information based on soil use capacity, water availability and the scarcity of high land for agricultural use. The costs of machinery allocated to the different operations at Elvas are summarized in Table 1. The data were available from market consultation. Overhead costs including administrative, marketing, and supervision tasks contributed to 3% of total costs.

A 30 cm deep fertilizing of 180 Kg ha^{-1} NPK 7:14:14 (7% N: 14% P_2O_5: 14% K_2O) in Elvas, is assumed prior to the plantation (establishment) followed by a surface fertilization after the first three harvestings. We assumed that after the third rotation a dynamic equilibrium was reached, under which most of the nutrients of the leaves are annually returned and recycled to the soil. Simultaneously the root system is sufficiently developed to provide an adequate nutrient absorption by the SRC crop. In Elvas a diurnal irrigation of 10 m^3 ha^{-1} is applied during 8 hours at night, in the three month summer periods over the entire lifespan of the cultivation. This water input with a SAP supplement was considered of the same order of magnitude as the water consumption by the poplar SRC. Two SAP applications of 15 kg ha^{-1} and 30 cm deep in the space between rows were also made. The SAP application is intended to retain soil water up to 5 m^3 ha^{-1} in the inter-row space, and supply it to the plants under successive sorption/desorption cycles. The conjunction of irrigation with SAP application was assumed to guarantee the necessary water for SRC consumption. The first SAP application was made simultaneously with the first fertilization, by mixing fertilizer with polymer. A second application was planned to be made after nine years, with a mechanical weed control following the third rotation.

Table 1- *Overview of the costs and characteristics of the machinery used in the poplar short rotation coppice in Elvas (data obtained by direct market consulting) d/o = depending on operation; n.a = no data used*

	Purchase Price (k€)	**Use (h year -1)**	**Lifetime (y)**	**Maintenance costs (€ h^{-1})**	**Salvage use (k €)**	**Fuel use (l h^{-1})**	**Operation rate (h ha^{-1})**	**Combined tractor**
Tractor 1	88	800	12	9.33	25	d/o	d/o	
Tractor 2	265	800	12	13.4	54	d/o	d/o	
Subsoiler (mole ploughing)	14.8	125.0	20	3.0	4	19.0	1.0	tractor 1
Plough	14.8	75.0	20	4.8	4	16.7	0.3	tractor 1
Harrow	14.8	100	10	3.4	4	20.0	0.2	tractor 1
Line cultivator	22.0	250	10	5.8	6.5	16.0	1.0	tractor 1
Leek planting machine	11.0	150	10	6	3.8	6.1	0.9	tractor 1
Rotary cultivator	60.0	150	10	35.6	17	25.0	2.0	tractor 2
Spraying equipment	6.0	200	10	10.1	3	16.7	0.3	tractor 1
Fertilizing equipment	2.9	100	10	5	1	16.0	1.0	tractor 1
Irrigation equipment	5.0	720	20	-	2	-	1.7	-
Trailer - $40m^3$	16.8	800	10	15.6	5	30.0	n.a	tractor 1

Model structure

The cost-benefit analysis of the poplar SRC cultivation was performed with the spreadsheet model POPFINUA (KASMIOUI and CEULEMANS, 2013) developed for a detailed analysis of the profitability and cost structure of these cultivations and optimized for inclusion of drip irrigation and application superabsorbent polymer (SAP) in the Elvas site. The economic feasibility of the cultivation is evaluated on a hectare unit area basis. The model consists of four different data input sheets. The first one is dedicated to the input of general assumptions (Figure 1) regarding land area, land costs, assumed annual biomass increments in the several rotations, rotation length, number of rotations, discount rate, overhead costs as percentage of yearly costs, biomass sales price and government incentives (subdivided in establishment grants and yearly benefits). The other three input sheets concern the establishment, the maintenance and the harvest. In each sheet the inherent costs of labour, equipment and materials (*e.g.*, chemicals) allocated to the respective operations are included. Machinery costs include maintenance, fuel, salvage and transport values. In was assumed that the farmer owns equipment for operations as ploughing, harrowing, planting, fertilizing, weed control, irrigation, SAP application and collection of the wood chips during harvest.

The establishment cost sheet uses input data regarding the site preparation, planting, and chemical herbicide. In the maintenance sheet mechanical weed control, drip irrigation, SAP application, fertilization and stump removal at the end of the plantation lifetime are considered. The harvest sheet includes the costs of the cutting operation and the transport of wet chips to the farm gate. The machinery option assumed for the harvest operation was the self-propelled New Holland harvesting-chipping machine (BERHONGARAY *et al.,* 2013). The harvesting equipment was rented, as the area involved did not justify the purchase of the expensive harvesting equipment. Table 2 presents the yearly implementation of the unit operations of the SRC cultivation along a 15 year lifecycle.

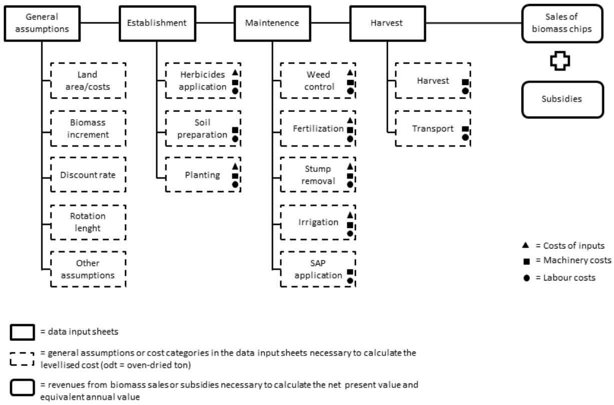

Figure 1 *- Schematic flow chart of the POPFINUA model for the simulation/calculation of the financial balance of a poplar short rotation coppice (adopted from EL KASMUIOUI and CEULEMANS, 2012)*

Table 2 *- Main unit operations for the 15 year lifecycle of the poplar SRC cultivation in Elvas*

Cost item/plantation year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Pre-emergent herbicide	Y														
Soil preparation	Y														
Post-emergent herbicide	Y														
Planting	Y														
Mechanical weed control									Y						
Harvest			Y			Y			Y			Y			Y
Fertilization	Y		Y			Y			Y						
Stump removal															Y
Land rent	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Irrigation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
SAP aplication	Y								Y						

SRC = Short Rotation Coppice
SAP = Supabsorbent polymer

The model allowed, through successive runs, to perform a sensitivity analysis on several key variables affecting the feasibility of the poplar SRC, namely biomass yield, land costs, discount rate, biomass price and establishment costs and annual incentives. Refer to KASMIOUI and CEULEMANS 2013, for a more detailed analysis of the simulation methodology.

Model outputs and financial metrics

The model output is based on the calculation of three financial metrics advisable for analysis of the economic feasibility of SRCs. These metrics are the Net Present Value (NPV), the Equivalent Annual Value (EAV) and the Levellised Cost (LC) (e.g., KASMIOUI and CEULEMANS, 2012; HAUK *et al*., 2014). The model allows also a graphical display of the yearly variation of NPV and cost structure components. The NPV is used to express future inputs and outputs of cash associated with a particular project in their present value, by taking into account the effect of the time delay of the revenues up to high cultivation lifetimes (e.g., 20 or 30 years) though application of an appropriate discount rate. The discount rate reflects the risk that a farmer assumes when opting by a given cultivation, taking in account the inflation rate, the market interest rate and a minimum yearly return rate considering the risks subjectively assumed. Decreasing the discount rate reduces the influence of present costs and benefits, while increasing the influence of future benefits in the project. A discount rate of 4% was assumed as a standard based value.

EAV combines the present value with an annuity factor to give a single annual sum equivalent to all considered cash flows, considering costs and benefits, uniformly distributed over the entire lifetime. EAV allows thereby comparing the annual cash-flows of projects with different lifetimes such as SRCs cultivations with traditional annual agricultural crops. LC gives the unique breakeven cost price for the woody biomass chips where discounted revenues are equal to discounted expenditures. This metric, if calculated as the price per energy unit, is a baseline that can be used to compare the cultivation costs of SRCs with the costs of other energy crops or energy carriers. Nowadays, for example in Iberian countries, the difference between the payments necessary to making investments profitable and the market price of electricity is the margin to be filled by the consumers to allow the use of renewable energies. So, the balance between the financial support for renewable energies and the market price may be positive, nil or negative resulting in additional charges, neutrality or savings in the electrical systems. Actually, this margin is positive resulting in fees paid by the consumer, but the predictions available point to an inversion of this tendency by 2040-50, when the market price will be enough to support the production costs (ROSET *et al.,* 2010).

Results

Cost structure

The financial results showed a period of profitability or lifecycle of 15 years, corresponding to 5 cycles of three year harvesting, (Figure 2) for achieving a limited NPV of 77€ ha^{-1}. In terms of costs per energy unit at the end of plantation lifetimes, the predicted value was 2.8€ GJ^{-1} at farm gate, above the threshold of the average delivered cost of coal at plant gate, i.e., 1.2€ GJ^{-1}. These costs fall also on the typical 0.8 to 5€ GJ^{-1} range considered for SRC production costs (KASMIOUI and CEULEMANS, 2012). The total costs of the operations of fertilizing, irrigation and polymer application in Elvas, after the plantation lifetime were totalized 595€ ha^{-1}. Based on market research we assumed a selling price of 40€ Mg^{-1} of biomass chips with 50% moisture content (m.c.) in both sites. This corresponds to price of about 80€ Mg^{-1} for dried biomass woody chips. The levellised cost (LC) was 79€ Mg^{-1} a bit lower than the biomass market price (80€ Mg^{-1}).

The cost structure in € per hectare for all the cultivation lifecycle is indicated in Figure 3. Maintenance costs, including fertilizing, mechanical weeding, irrigation, polymer application and stump removal at the end of the 15 year lifecycle, corresponded to 9% of total costs, or 800€ $hec.^{-1}$. The establishment costs including herbicide application, soil preparation through plough and harrowing and plantation at a one row and 6700 plants/hect, corresponded to 18% of the costs (1480€ $hec.^{-1}$). General costs including land rate and overheads corresponded to 29% of costs (2430€ $hec.^{-1}$). Finally, harvesting costs included the rental of harvesting equipment the respective operation and the field transport of biomass chips to farm gate, with a minimum impact, corresponded to 44% the total costs (3770€ $hec.^{-1}$).

The impact of labor costs is reflected *e.g.*, by the weights of 2.9% and 16% of wages in the establishment and management costs respectively corresponding to averages of 43€ and 73€ for each set of the corresponding operations, respectively.

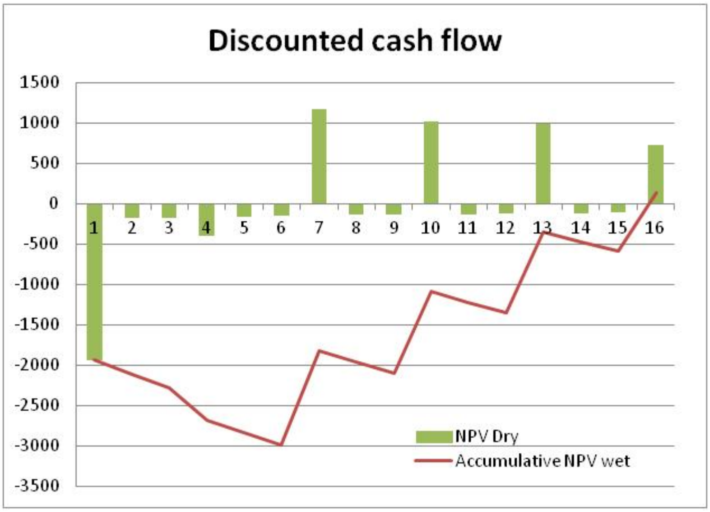

Figure 2 - *Simulated discounted yearly cash flows and accumulated discounted cash flow for Portuguese scenario for a short rotation woody crop plantation with a 3-year rotation and a total lifetime of 15 years*

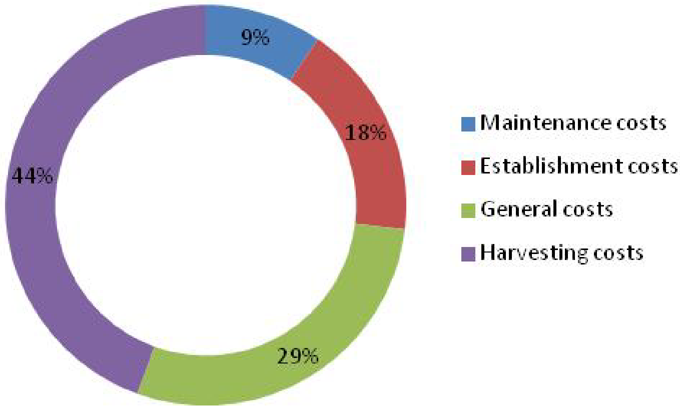

Figure 3 - *Simulated cost structure of the SRC cultivation*

Sensitivity analysis

Biomass yield

Concerning the biomass yield the calculation showed that a biomass yield variation from 12 Mg ha^{-1} $year^{-1}$ to 15 Mg ha^{-1} $year^{-1}$ (by 25%) would trigger a threefold increase of % in NPV over the cultivation lifetime and a correspondent decrease of 23% on LC (Figure 4). This relevant impact of the biomass yield in the financial results of the SRC cultivation, illustrates the relevance of the continuous optimization of the cultivation technology to improve the yield.

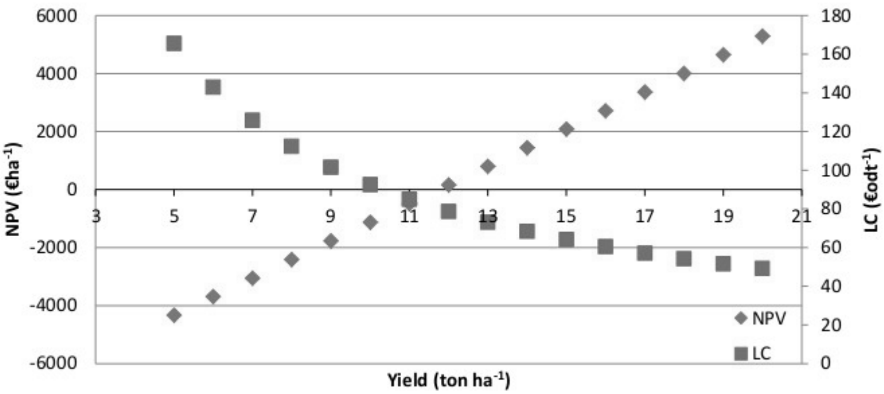

Figure 4 *- Results of the sensitivity analysis showing the impact of biomass yield on the net present value (NPV) and the levellised cost (LC) per oven-dried ton (odt) of a short rotation coppice culture from the POPFINUA model runs*

Land rent costs

The land rent costs also have a major impact on the profitability of the cultivation. As expected, NPV decreases with land rent costs (Figure 5). An increase in land rent price from 50 to 150€ ha^{-1} $year^{-1}$ would be reflected by a decrease of 91% on NPV and 24% on LC. On the other hand, an increase in the land rent price from 180 € ha^{-1} to 190€ ha^{-1} would be reflected by a decrease of NPV of about 125€ ha^{-1} turning the SRC unprofitable.

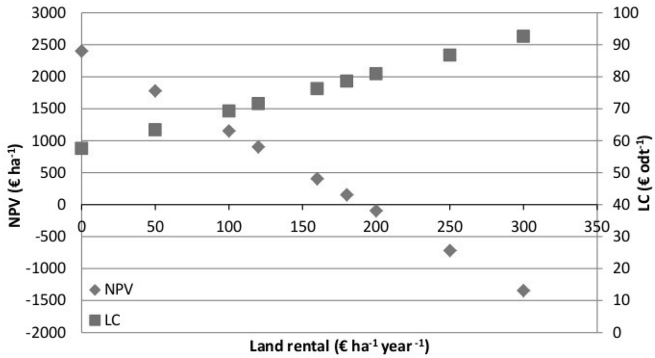

Figure 5 - Results of the sensitivity analysis showing the impact of land costs on the net present value (NPV) and the levellised cost (LC) per oven-dried ton (odt) of a short rotation coppice culture based on the POPFINUA model runs

Discount rate

The standard discount rate assumed to evaluate to the break-even point was 4%. As expected the net present value decreased with discount rate, whilst levellised cost increased with it (Figure 6). However, LC increase was much less sensitive than NPV to discount rate variation than NPV. Indeed, an increase in discount rate by 4 steps of 1% per year (1% till 4%) was reflected on an average decrease of 30% in NPV by each step and a simultaneous constant increase of 2% in LC.

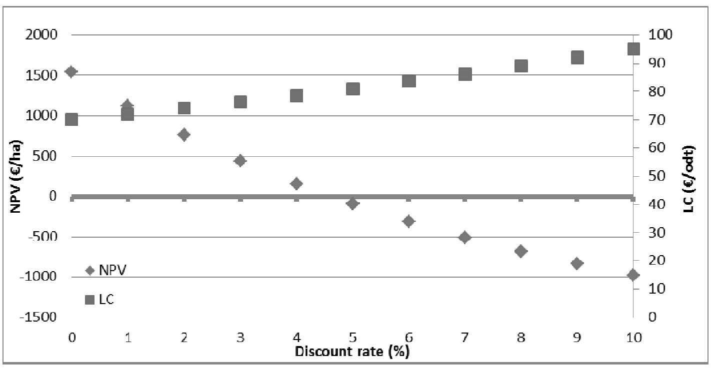

Figure 6 - Results of the sensitivity analysis showing the impact of the discount rate on the net present value (NPV) and the levellised cost (LC) of a short rotation coppice culture from the POPFINUA model

Establishment grants and annual incentives

In Elvas, the NPV increased with annual subsidies whilst stagnating with establishment grants. The average increase of NPV, in the range of 0-200€/hect of per € of annual subsidy was 15€. The advantage of annual subsidies over establishment is due to its attribution along every year of the cultivation.

Figure 7 shows that the farm gate price for biomass chips to reach break-even at the baseline scenario should be at least of the order of 40€ Mg^{-1}. To evaluate the impact of biomass price it can be mentioned that an increase of the biomass price by 1€ Mg^{-1}, according to this model, would result in an increase NPV by 280€ ha^{-1}, and EAV by 25.3€ $ha^{-1}year^{-1}$, illustrating that both NPV and EAV were highly sensitive to the market demand. This sensitivity to price fluctuations points out the need to a coherent political strategy for implementing a sustainable market for biomass demand.

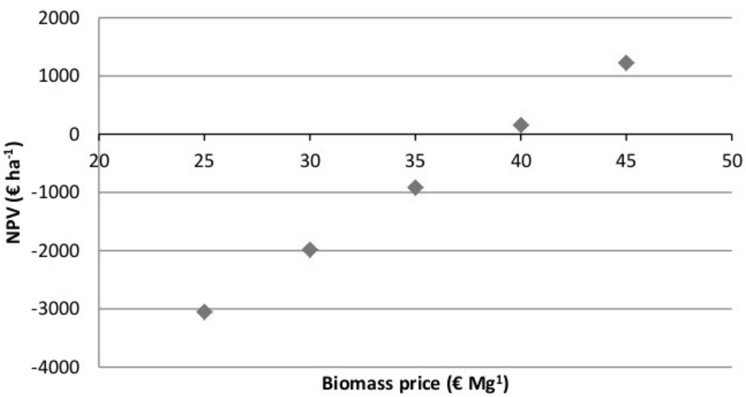

Figure 7 - *Results of the sensitivity analysis showing the impact of the biomass price (50% moisture content) on the net present value (NPV) of a short rotation coppice culture based on POPFINUA model runs*

Discussion

The results showed a plantation lifecycle of 15 years to achieve a positive NPV of 77€ ha^{-1}. This is a small value comparatively to more relevant food crops. The SRC plantation must thereby be installed in soils with low or medium fertility, without agricultural potential, in order to do not try to compete with more profitable food crops. The 15 year lifecycle period is small in European terms, comparing *e.g.* with 21 years in a poplar SRC cultivation in Lochristi, Belgium (KASMIOUI and CEULEMANS, 2013), and the low labor and rental costs are certainly determinant to that result. Indeed the labor costs considered in this work 10 and 12€ h^{-1} for agricultural labourer and foreman are well below the correspondent values of 35 and 40€ h^{-1}, in Belgium respectively. Also the land rental of 180€ h^{-1} is significantly smaller than the correspondent 250€ h^{-1} considered for Belgium.

The total costs of the operations of fertilizing, irrigation and superabsorbent polymer application, were estimated respectively as 353€ ha^{-1}, 177€ ha^{-1} and 66€ ha^{-1}, after the plantation lifetime. These costs contributed to the estimated 9% share of the total costs for maintenance operations, which are close to the average of 10% indicated by HAUK *et al.* 2014, but below the correspondent 2% for the same costs in Belgium (KASMIOUI and CEULEMANS, 2013) where the operations of fertilizing, irrigation and superabsorbent polymer application are not considered. As mentioned, these additional operations are necessary to address water stress in summer, a situation typical of Mediterranean climates, as well to meet possible nutrient requirements in less fertile soils. The establishment costs (15% in of the total) are similar to the correspondent 16% in the study for Lochristi, Belgium, and are lower than the average referred in HAUK *et al.,* 2014 perhaps due to the aforementioned distinct criteria for cost evaluation. The harvesting costs, corresponding to 44% of the total costs, are close to the average reported costs of 46% in the Belgium study, and are also of the same order of magnitude for the 43% due to harvesting and biomass chips field transport to farm gate reported by the study of HAUK *et al.,* 2014. The costs per energy unit at the end of plantation lifetime were 2.8€ GJ^{-1} at farm gate, comparing with 2.4€ GJ^{-1} for the Belgium study, and above the threshold of the standard average delivered cost of coal at plant gate, i.e., 1.2€ GJ^{-1}. These costs are within the range of 0.8€ GJ^{-1} to 5 € GJ^{-1} considered for SRC production costs (KASMIOUI and CEULEMANS, 2012).

The sensitivity analysis, made by the POPFINUA model runs, showed the relevance of variables such as the biomass yield, land rent price, annual grants and biomass price on the financial feasibility of the cultivation. In this respect, the biomass yield was shown as the more relevant variable. This conclusion agrees with the referred, e.g. by HAUK *et al*., 2014, wherein the price for biomass, wood chips or round wood is seen as the most important factor for the profitability of SRCs. For example, an increase in biomass yield of 25% from 12 Mg ha^{-1} $year^{-1}$ to 15 Mg ha^{-1} $year^{-1}$, a very realistic scenario, would cause a threefold increase of the NPV over the cultivation lifetime. This compares with the fivefold increase, under the same circumstances, reported by the Belgium study of KASMIOUI and CEULEMANS, 2013. Biomass yield increases with management, genetic and environmental variables and an investment on these variables would thereby ensure an adequate financial return. Biomass price was also a relevant variable. Indeed, an increase in of the biomass price by 1€ Mg^{-1}, would increase NPV by 280€ ha^{-1}, a value of the same order of magnitude as the reported by the Belgian study. Also of the same order of magnitude with this study was the average increase of NPV of 15€, estimated in this work, per € of annual subsidy in the range of 0-200€ $hect^{-1}$. The break-even dry matter price for biomass at the farm gate, calculated by the levellised costs was 79€ Mg^{-1} (dry biomass). The correspondent value for LC in the Belgium study was 78.4€ Mg^{-1}. These values are a bit smaller than biomass market price, (80€ Mg^{-1} for dried biomass). We think that these results of biomass selling prices are theoretical, given the market fluctuations, and thereby the issue of public support should be always addressed. Moreover the demand for bioenergy (e.g. co-firing in power plants or heat from steam boilers) must be promoted by incentives to long term maturation of the biomass markets. For example, in Portugal the forest biomass has figured as competitive to generate superheated steam for industrial small and medium textile companies, comparatively to natural gas (NUNES *et al.*, 2013a; NUNES *et al.,* 2013b). Another identified potential is the use co-firing technology with financial incentives in a thermal power plant in Southern Portugal, resulting in a reduction of 1 million tons/year of atmospheric CO_2 emissions with additional reduction in emissions of NO_x as well (NUNES *et al.*, 2014, PEREIRA *et al.,* 2016). So a policy to incentive the long term contracting between the SRC farmers and demand industries, should constitute a possible path to a SRC cluster development.

Conclusions

This study showed that the optimization of biomass yield of poplar SRC is essential for a commercial implementation of these cultivations. Thereby, conditions such as a throughout knowledge of the technologies of the operations, a logistical framework for availability of the necessary equipment and a mature market for biomass demand, are required. In this context a necessary condition is the implementation of research and extension field plots where the alternative solutions for the plantation lifecycle should be tested. In a context of global warming that implies a progressive application of renewable resources for bioenergy, Portugal is a country with distinct climate and soil characteristics, where the introduction of SRCs has huge potential. To fulfill this potential, financial conditions related to the optimization of profitability with or without public incentives must be implemented. Indeed, an adequate strategy of public support to SRCs should be implemented under a predictable scenario of climate change and fossil fuels scarcity. Besides grants and subsidies, this strategy should include commitments to increasing incorporation of SRC's biomass in the feedstock of heat and power plants. Incentives to implement water vapor or heated water for providing thermal energy for facilities and industrial companies should also be equated. Finally SRCs cultivations could help to contribute to sustain problems such as the desertification of rural areas through the diversification of economic activities.

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References

BERHONGARAY, G., KASMIOUI, O., CEULEMANS, R., 2013.Comparative analysis of harvesting machines on an operational high-density short rotation woody crop (SRWC) culture: One-process versus two-process harvest operation. *Biomass and Bioenergy* **58**: 333-342.

BLANCO, H., 2012. Cultivos Forestales para energía: caso del chopo. Communication presented in the *Advanced Course on-line "Cultivos forestales con aplicaciones energéticas"* April- May 2012, Cordoba University, Spain.

BLANCO, H.S., GARASA, M.J.H., CÍRIA, M.P.C., GARCIA, J.E.C., VINÃS I.C., 2010. *Manual de cultivo de populus spp. para la producción de biomasa con fines energéticos*. INITAA, 62pp. Madrid.

CASQUILHO, M., RODRIGUES, A., ROSA, F., 2013. Superabsorbent polymer for water management in forestry. *Agricultural Sciences* **4**: 57-60.

DI MATTEO, G., SPERANDIO, G., VERANI, S., 2012. Field performance of poplar for bioenergy in southern Europe after two coppicing rotations: effects of clone and planting density. *Iforest-Biogeosciences and Forestry* **5**:224-229 doi: 10.3832/ifor0628-005.

DILLEN, S.Y., STEWART B.R., CEULEMANS R., 2010. *Growth and Physiology* 39-63, 2010. in Genetics and Genomics of Populus, Editors: Jansson, S., Bhalerao, R., Groover A. (368 pp.) ISBN: 978-1-4419-1540-5, Springer.

DJOMO, S.N., EL KASMIOUI, O., CEULEMANS, R. , 2011. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *Glob Change Biol Bioenergy* **3**(3):181–197. doi:10.1111/j.1757-1707.2010.01073.x.

EL KASMIOUI, O., CEULEMANS, R., 2012. Review. Financial analysis of the cultivation of poplar and willow for bioenergy. *Biomass and Bioenergy* **43**: 52-64.

El KASMIOUI, O., CEULEMANS, R., 2013. Financial analysis of the cultivation of short rotation woody crops for bioenergy in Belgium: barriers and opportunities. *Bioenergy Research* **6**: 336-350.

GASOL, C.M., MARTÍNEZ, S., RIGOLA, M., RIERADEVALL, J., ANTON, A., CARRASCO, J., CIRIA, P., GABARREL, X, 2009. Feasibility assessment of poplar bioenergy systems in the Southern Europe. *Renew Sust Energ Rev* **13**: 801-12.

GONÇALVES, M.S., 2010. *Análise Ambiental e Energética da produção de Eucalyptus Globulus para conversão em energia eléctrica*. Dissertation for MsC Deg. Env. Eng., 2010, IST, Lisbon, 79 pp.

HAUK S., KNOKE T., WITTKOPF S., 2014. Economic evaluation of short rotation coppice systems for energy from biomass -A review. *Renew Sustain Energy Rev* **29**: 435-448. doi: 10.1016/j.rser.2013.08.103.

HÜTERMANN, A., ORIKIRIZA, L., AGABA, H., 2009. Review. Application of superabsorbent polymers for improving the ecological chemistry of degraded or polluted lands. *Clean* **37**(7): 517-526.

ICNF, 2013. Inventário Florestal Nacional (Portugal Continental) Lisboa. http://www.icnf.pt/portal/ florestas/ifn/resource/ficheiros/ifn/ifn6-res-prelimv1-1.

INTERNATIONAL ENERGY OUTLOOK, 2014. Energy Information Administration, November 2014, http://www.worldenergyoutlook.org/publications/weo-2014.

KAHLE, P., HILDEBRAND, E., BAUM C., BOELCKE, B., 2007. Long term effects of short rotation forestry with willows and poplar on soil properties. *Archives of Agronomy and Soil Science* **53**: 673-682.

LADANAI, S., VINTERBÄCK, J., 2009. *Global potential of sustainable biomass for energy*. Report 013, ISSN 1654-9406Swedish University of Agriculture and Sciences, Department of Energy and Technology, Uppsala.

MARTINEZ, M., 2012a. Cuidados culturales en cultivos energéticos: nociones de fertilización e rego. Huelva University, Dep. of Agroforestry Sciences. Communication presented in the *Advanced Course on-line "Cultivos forestales com aplicaciones energéticas"* April- May 2012, Cordoba University, Spain.

MARTINEZ, M.F., 2012b. Experiencia de la UHU con cultivos de species lenhosas en rotaciones cortas com destino energético. Huelva University, Dep. of Agroforestry Sciences. Communication presented in the *Advanced Course on-line "Cultivos forestales com aplicaciones energéticas"* April- May 2012, Cordoba University, Spain.

NUNES L., MATIAS J., CATALÃO J., 2013a. Economic evaluation and experimental setup of biomass energy as sustainable alternative for textile industry. In: *2013 48th Int. Univ. Power Eng. Conf. IEEE*: pp. 1-6.

NUNES L., MATIAS J., CATALÃO J., 2013b. Application of biomass for the production of energy in the Portuguese textile industry. 2013 Int. *Conf. Renew. Energy Res. Appl. IEEE*: pp. 336-341.

NUNES, L., MATIAS, J., CATALÃO, J., 2014. Biomass waste co-firing with coal applied to the Sines power plant in Portugal. *Fuel* **132**: 153-157.

OTERO, J., ARRIETA, J., 2012. Cultivos energéticos: Análisis da la cadena de valor de los C.E. y principales variables para assegurar la sostenabilidad económica a largo plazo. Communication presented in the *Advanced Course on-line "Cultivos forestales com aplicaciones energéticas"* April- May 2012, Cordoba University, Spain.

PARIS, P., MARESCHI, L., SABATTTI, M., PISANELLI, A., ECOSSE, A., NARDIN, F., SCARASCIA-MUGNOZZA, 2011. Comparing Hybrid Populus clones for SRF across Nothern Italy after two biennal rotations: survival, growth and yield. *Biomass and Bioenergy* **35**: 1524-1532.

PEREIRA, S., COSTA, M., CARVALHO, M.G., RODRIGUES, A., 2016. Potential of poplar short rotation coppice cultivation for bioenergy in Portugal. *Energy Conversion and Management* 12 pp, article in press.

PITA, G., GIELEN, B., ZONA, D., RODRIGUES, A., RAMBALD, S., JANSSENS, I., CEULEMANS, R., 2013. Carbon and water vapor fluxes over four forests in two contrasting climatic zones. *Agricultural and Forest Meteorology* **180**: 211-224.

RAJU, M., RAJU, M., 2001. Synthesis of novel superabsorbing copolymers in agricultural and horticultural applications. *Polymer International* **50**: 946-951, doi:10.1002/pi721-

RODRIGUES, A., BORDADO, J., MARGARIDA, M., 2015. An evaluation of SRCs as a Potential carbon neutral source of biomass for energy and Chemicals Advances in *Environmental Series* **43**: 79-143.

RODRIGUES, A., PITA, G., MATEUS, J., KURZ-BESSON, C., CASQUILHO, M., CERASOLI, S., GOMES, A., PEREIRA, J., 2011. Eight years of continuous carbon fluxes measurements in a Portuguese eucalypt stand under two main events: Drought and felling. *Agricultural and Forest Meteorology* **151**: 493-507.

ROSET, J., FERNANDEZ, L., RUBIRA, J., 2010. *Evolution tecnológica e prospectiva de costes de las energias renovables*. Boston Consulting Group. Edited by the Instituto para la Diversificación y Ahorro de la Energia, Technical Studies PER 2011-2020.

SCHWEIER, J., BECKER, G., 2013. Economics of poplar short rotation coppice plantations on marginal land in Germany. *Biomass and Bioenergy* **59**: 494-502.

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Aplicações Industriais da Resina de *Pinus pinea*

Miguel Pestana

Sumário. O *Pinus pinea* suporta bem frios não muito intensos e apreciável secura, mas exigindo temperaturas médias anuais superiores a 10-11ºC, prospera em zona de pluviosidade anual compreendida entre 400-800 mm, as quais no nosso país, correspondem já a situações de acentuada secura, nomeadamente no período estival. Prefere terrenos soltos ou arenosos e frescos, mas adapta-se bem a outros tipos, nomeadamente os calcários.

Em Portugal, ocupa uma área de 175.742 ha, com 38,3% na região NUT III – Alentejo Litoral e o seu principal valor económico direto é o pinhão.

O aumento da área em 46% da área total nos últimos 15 anos em Portugal mostra a importância desta espécie florestal. Com um lento crescimento e um baixo valor da sua madeira comparada com o *Pinus pinaster* e, por outro lado, com a não exploração da resina, o que interessa para a região é o valor comercial do pinhão.

Hoje em dia os povoamentos têm-se modificado. Damos importância à resina, pelo que explicamos em mais detalhe as aplicações da Aguarrás e da Colofónia (Pez)

Como resultando da destilação da resina de *Pinus pinea* e da análise cromatográfica da sua Aguarrás e Pez, é possível conhecer os seus principais componentes, que promovem este produto.

A resina de pinheiro manso tem propriedades distintas relativamente a outras resinas, nomeadamente na baixa viscosidade, elevada cristalização espontânea e baixos teores em monoterpenos, mas também possui uma elevada percentagem em limoneno, o qual torna interessantes as suas aplicações na indústria química.

A presente contribuição enaltece as aplicações da resina de pinheiro manso na indústria.

Palavras-chave: Resina de pinheiro, colofónia, aguarrás, derivados, composição química, aplicação industrial

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The industrial applications of *Pinus pinea* resin

Abstract. *Pinus pinea* supports well not intensive and significant dryness, but requires annual average temperatures above 10-11ºC, thrives at annual rainfall between 400-800 mm, corresponding to situations of severe drought, particularly in summer. It prefers sandy and fresh soils, but adapts well to other types, including calcareous soils.

In Portugal, it occupies an area of 175,742 ha, with 38.3% in the region NUT III - Alentejo Litoral, and its main direct economic value are pine nuts.

The increase of area in 46% of the total area in the last 15 years in Portugal shows the importance of this forest specie. With a slow growth and a low value of its wood, compared to *Pinus pinaster*, and on other hand with resin not in use, it is the commercial value of the pine nuts that interested in the region.

Today the status has changed. We give importance to the resin so we explain in more detail, the applications of turpentine and rosin.

Resulting from distillation of *Pinus pinea* resin and chromatographic analysis of its turpentine and rosin, it's possible to know what its main components, then we given the most important applications that enhance this resin.

Stone pine resin has distinct properties from others resins, namely in lower viscosity, higher spontaneous crystallization and lower content of monoterpenes, but higher percentage of limonene, which makes its application in chemical industry interesting.

The present contribution highlights applications of stone pine resin in industry.

Key words: Pine resin, rosin, turpentine, derivates, chemical composition, industrial application

Applications industrielles de la Resine de *Pinus pinea*

Résumé. *Pinus pinea* supporte le froid et une sécheresse pas très importante et intense, mais nécessite des températures annuelles moyennes supérieures à 10-11ºC. L'espèce est favorisée dans les zones de précipitations annuelles entre 400 et 800 mm, ce qui représente dans notre pays des conditions de sécheresse sévère particulièrement en été. *Pinus pinea* préfère la terre meuble ou sablonneuse et fraîche, mais s'adapte bien à d'autres types de sol, y compris calcaire.

Au Portugal, cette espèce occupe une superficie de 175.742 ha, avec 38.3% dans la région NUTS III - Alentejo Littoral, et sa valeur économique directe principale est le pignon.

L'augmentation de 46% de la superficie total au cours des 15 dernières années au Portugal, montre l'importance de cette espèce forestière. C'est avec une croissance lente et une faible valeur de son bois, par rapport à *Pinus pinaster*, en plus de la non-exploitation de la résine, que la valeur commerciale du pignon compte pour la région.

De nos jours, les pinèdes ont été modifiées. Nous accordons une importance à la résine, de sorte que nous expliquons plus en détail l'application de térébenthine et de la colophane.

Issu de la distillation de la résine de *Pinus pinea* et de l'analyse chromatographique de son térébenthine et sa colophane, vous pouvez connaître leurs principaux composants, ce qui promeut cette résine.

La résine de ce pin a des propriétés différentes par rapport à d'autres résines, en particulier une faible viscosité et une haute cristallisation, de faibles niveaux de monoterpènes, mais un pourcentage élevé de limonène, ce qui rend leurs applications intéressantes pour l'industrie chimique.

Cette contribution exalte les applications de l'industrie de la résine de *Pinus pinea*.

Mots-clés: Résine de Pin, colophane, térébenthine, dérivés, composition chimique, application industrielle

Introdução

Desta espécie florestal podemos retirar uma variedade de produtos, todavia iremos focalizar num dos seus produtos – a resina ou gema. Iremos pois fazer uma resenha das suas aplicações na indústria química e serão referenciadas outras aplicações pouco conhecidas, de alguns dos produtos.

Sendo o *Pinus pinea* uma árvore com expressão no sul de Portugal, no entanto as suas características têm sido pouco exploradas. Este pinheiro "é claramente termófilo e muito heliófilo, suportando bem frios não muito intensos e apreciável secura, mas exigindo temperaturas médias anuais superiores a 10-11ºC, prospera em zona de pluviosidade anual compreendida entre 400-800 mm, as quais no nosso país, correspondem já a situações de acentuada secura, nomeadamente no período estival. Prefere terrenos soltos ou arenosos e frescos, mas adapta-se bem a outros tipos, nomeadamente os calcários" (CESE, 1996).

Com uma área ocupada de 175.742 ha (Inventário Florestal Nacional – IFN6), estando no distrito de Setúbal a sua maior área e tem como seu principal valor económico direto o pinhão. Este tem uma grande procura internacional, motivada pelas suas características e qualidade.

A gema, obtida da resinagem do pinheiro manso, pode ser destilada por arrastamento de vapor, obtendo-se uma fração volátil – aguarrás – e outra fração pesada – pez ou colofónia. O valor da fração volátil (aguarrás) desta operação (destilação) é próximo dos 10%.

Acreditamos ser importante, ilustrar as aplicações dos produtos da 1ª transformação da Resina (Gema) - a Aguarrás e o Pez (Colofónia). A gema possui propriedades distintas das do pinheiro bravo, nomeadamente quanto à menor viscosidade, maior cristalização espontânea, menor teor em monoterpenos, próximo dos 10% (CARVALHO, 1986), mas muito maior percentagem de limoneno, o que a torna interessante para a perfumaria e não só. Este constituinte, para além da sua aplicação em aromas e fragrâncias quer em bruto quer através de carvona (produto de síntese), pode também ser utilizado como solvente para tintas e vernizes, como elemento importante no processamento de borracha, como inseticida e ainda, em produtos de limpeza (SILVA, 1991). O dipenteno (a mistura *d* e *l* limoneno) serve de ponto de partida para a obtenção de outros produtos de síntese, dos quais achamos importante enumerar o p-cresol (utilizado como antioxidante de borrachas), os ésteres fenilterpénicos (usados na produção de adesivos epóxidos resistentes à água e na produção de pastilhas elásticas), as resinas dipenténicas (aplicadas principalmente em adesivos e colas papeleiras, como componente em borracha e como protetor de superfícies), o "petrex" (usado em resina, tintas e celofane) e ainda o hidroperóxido de p-mentano (iniciador da polimerização de borracha estireno-butadieno - SBR) (SILVA, 1991).

O ácido levopimárico está presente com valores superiores a 30% da fração ácida da colofónia de pinheiro manso (CARVALHO, 1986), tendo como principais utilizações na indústria química: na síntese de hormonas vegetais do tipo giberelinas (indicadas pelas suas propriedades fisiológicas), na obtenção de compostos biologicamente ativos, como são exemplo os sais de sódio do ácido fumaropimárico utilizados para prevenir a rejeição de enxertos de pele ou ácido maleopimárico precursor de maleopimarimidas N-substituídas, cujos derivados foram patenteados como sendo úteis na Medicina e Agroquímica; ou ainda, todos os produtos de síntese resultantes da transformação deste ácido em ácido abiético (GIGANTE *et al.*, 1987). A Colofónia (Pez) proveniente da gema de pinheiro é utilizada tradicionalmente na produção, por exemplo, de linóleos, vernizes, adesivos e tintas de impressão, devido às suas importantes propriedades: impermeabilidade; brilho; resistência a abrasão; propriedades adesivas e filmogénicas (LOMBARD, 1946; ZINKEL *et al.*, 1989).

Muito embora, esta espécie tenha um vasto campo de aplicações julgamos que a sua aguarrás, tem potencialidades na indústria química.

A aguarrás

Avaliando os resultados obtidos pela análise cromatográfica, verifica-se que este produto (aguarrás de *pinus pinea*) é rico em limoneno (FIGUEIREDO *et al,* 2014), o que lhe possibilita um vasto campo de aplicações na indústria química e em aromas e fragrâncias na perfumaria.

Realçando o interesse destes produtos é possível referir que a sua utilização mais habitual é como solvente de tintas e vernizes, sendo ainda importante para o amolecimento e processamento de borrachas, também como produto de limpeza (KARR *et al.*, 1988) e inseticida (PESTANA, 2011; TAYLOR *et al.*,1983). Também tem vindo a ser testado como produto de preservação de madeiras de pinho destinado a combater os fungos decompositores *Trametes versicolor* TR 489 e *Trichodermacitrinoviridae*B2, onde os resultados até aqui obtidos são bastante satisfatórios (ANJOS, 2009).

Uma outra aplicação deste constituinte principal da aguarrás de pinheiro manso está associada à reciclagem de poliestireno, onde desempenha um papel de solvente desse polímero apresentando propriedades antioxidantes do limoneno, sendo a separação desses dois compostos da mistura feita por vácuo.

Como o limoneno é um dos constituintes do dipenteno (a mistura *d* e *l* limoneno), é possível obter-se um espectro mais alargado de derivados. Este produto pode ser hidrogenado obtendo-se p-cimeno, do qual se pode alcançar o p-cresol (DEFER, 1978; DUPONT, 1926; SKOLNIK, 1963; TAYLOR *et al.*, 1983), produto utilizado como anti-oxidante em borracha (Figura 1). O dipenteno é também utilizado para produzir ésteres fenilterpénicos usados para a produção de adesivos epóxidos resistentes à água (SEDEL'NIVOK *et al.*, 1985), é também usado como base para a produção de pastilhas elásticas e como constituinte de certos revestimentos para alimentos (DEFER, 1978).

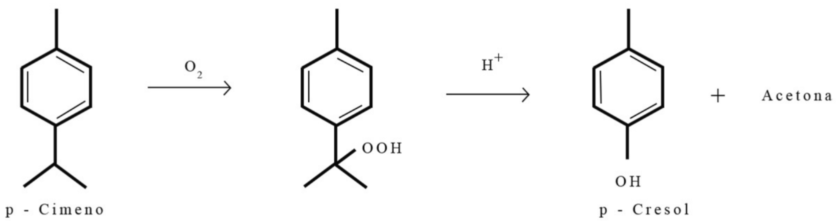
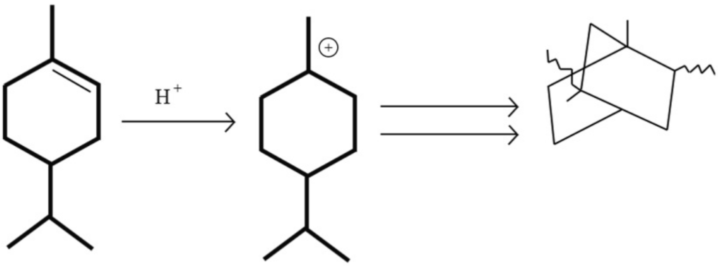


Figura 1 *- Sequência reacional para a produção do p-cresol a partir p-cimeno*

Caso o dipenteno sofra uma polimerização catiónica, obtemos resinas dipenténicas, as quais são aplicadas em adesivos e em colas papeleiras, como componente em borracha e como protetor de superfícies. O passo inicial desta reação é desencadeado com o ataque de um protão à ligação dupla externa ao anel, havendo diversas especulações para a reação de propagação de polimerização. A mais consistente refere que a reação prossegue com o ataque à posição trisubstituída do anel pelo carbocatião, sofrendo uma polimerização cíclica, que nos conduz a uma unidade estrutural como a exibida na Figura 2 ou ainda, mais provável, será o ataque do carbocatião isopropil pendente à ligação dupla residual da penúltima unidade "mer" (unidade repetitiva de uma cadeia polimérica) e assim forma um anel com o subsequente processo de polimerização - Figura 2 (RUCKEL *et al.*, 1984, 1984a; STAROSTINA *et al.*, 1987; TAYLOR *et al.*,1981, 1983; ZINKEL *et al.*, 1989).



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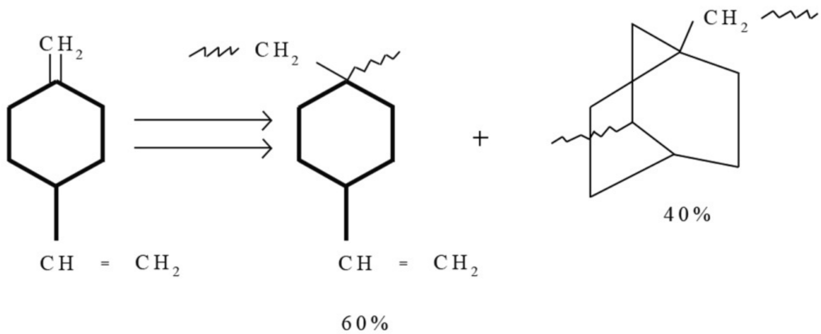

Figura 2 *– Possíveis caminhos de propagação para a polimerização do Dipenteno*

Pela hidrogenação do dipenteno obtemos o p-mentano, que se transforma em hidroperóxido na presença de oxigénio molecular. Este produto é usado como iniciador da polimerização das borrachas SBR. Caso o dipenteno seja isomerizado, ele dará uma mistura que contém α-terpineno, o qual combinado com anidrido maleico sofre uma reação de Diels-Alder para se alcançar o "petrex" (Figura 3), produto utilizado em resinas, em tintas e em celofane (DEFER,1978).

Na área de aromas e fragrâncias, o limoneno (neste caso, *l*-limoneno) é usado para a produção de carvona. Contudo, a indústria de citrinos oferece uma fonte alternativa de *d*-limoneno de elevada pureza ótica. Este material pode ser refinado para que ofereça a qualidade do perfume ou pode ser usado como composto químico intermediário. O *d*-limoneno é principal produto de partida para a preparação de (-) carvona. A reação do *d*- limoneno com cloreto de nitrosilo resulta numa adição seletiva da ligação dupla altamente substituída de cloreto nitroso de limoneno. Alerta-se que esta mistura reacional, para 40 a 50^0C, provoca a eliminação de ácido clorídrico e um rearranjo exotérmico do grupo nitroso para produzir carvoxima. A hidrólise deste composto resulta então em (-) carvona, o qual é o principal componente do óleo da hortelã. Se o produto de partida for o *l*-limoneno, então teremos como produto final o (+) carvona. Este enantiómero da carvona não tem aroma a hortelã, mas, em vez disso, tem odor e sabor a Endro (TAYLOR *et al.*,1983; ZINKEL *et al.*, 1989).

A Colofónia (Pez)

Em contraste com a aguarrás, na qual muitos das suas utilizações são baseadas nos seus componentes *per si,* pelo que a sua separação é importante, o Pez é usado como um todo, sem qualquer posterior fracionamento.

A Colofónia é uma mistura de ácidos resínicos com estrutura muito similar, sendo alguns isómeros. A relação das proporções dos vários isómeros pode ser alterada simplesmente pela aplicação de calor ou pelo tratamento com um ácido mineral.

O ácido levopimárico foi o principal constituinte da colofónia detetado pela análise cromatográfica da Colofónia de pinheiro manso. Pode ser isolado em larga escala, tem sido considerado como uma matéria-prima química. A metodologia de isolamento está baseada na cristalização preferencial do 2-amino-2-metil-1-propanol do ácido levopimárico como originalmente idealizado por HARRIS *et al.* (1948).

Pelos resultados obtidos da mesma análise cromatográfica, constata-se que a Colofónia é essencialmente constituída por ácidos resínicos (cerca de 90%) e uma fração neutra. Entre aqueles, o ácido levopimárico tem uma estrutura que assenta num esqueleto tipo do ácido abiético - mais reativo e, consequentemente, com maior aproveitamento industrial - diferindo somente na localização das suas duas duplas ligações.

A Colofónia pode ser submetida a tratamentos químicos - Colofónia Modificadas - visando a melhoria das suas propriedades e o aumento da sua estabilidade, quer pela alteração do posicionamento da ligação dupla, quer pela pelas reações do grupo carboxílico (CARVALHEIRO, 1986; GIGANTE *et al.*, 1987; LOURENÇO *et al.*, 1980; SAMPAIO, 1988; VEZES *et al.*, 1924; ZINKEL *et al.*, 1989).

Refira-se ainda que a Colofónia pode sofrer degradação térmica dos ácidos resínicos (descarboxilação), sendo o produto resultante o Óleo de Pez. Este tem aplicações no fabrico de cabos elétricos e na recuperação de borracha (LOMBARD, 1946; ZINKEL *et al.*, 1989).

Nos anos 40 do século passado, cerca de 30% do Pez era utilizado no fabrico de sabão amarelo em barra, produto que entrou em desuso com a entrada dos detergentes (CARVALHEIRO, 1986; LOMBARD, 1946).

Durante a Segunda Guerra Mundial, a indústria de produção de borracha sintética utilizou o Pez como agente emulsionante e espessante sob a forma de sabões de Pez Desproporcionado (CARVALHEIRO, 1986 LOMBARD, 1946; LOURENÇO *et al.*, 1980; ZINKEL *et al.*, 1989). Atualmente é utilizado no fabrico do polímero SBR ("Styrene-Butadiene Rubber") e EPT ("Ethylene Terpolymer") (ZINKEL *et al.*, 1989).

Mais tarde passou a utilizar-se no tratamento do papel ("Sizing"), a fim de controlar a absorção de água, sendo substituído por novos produtos mais competitivos (ZINKEL *et al.*, 1989).

Com o desenvolvimento industrial iniciado na década de 60 do século passado, foi possível conhecer, mais exatamente, a estrutura dos ácidos resínicos, o que permitiu a sua aplicação noutros domínios (Medicina, Perfumaria, Agroquímica, etc.), na obtenção de produtos químicos com aplicação na área dos polímeros e dos lubrificantes sintéticos e como intermediário de síntese de compostos biologicamente ativos (Esteroides, Hormonas, Inibidores Tumorais, entre outros).

Do conjunto de ácidos do tipo abiético, o ácido levopimárico pode sofrer modificações químicas pela reação de Diels-Alder. Esta envolve uma reação do composto carbonilo α-, β- insaturado, tais como o anidrido maleico, o ácido maleico ou o ácido fumárico, com uma ligação dupla conjugada, que levará à obtenção de um ácido tricarboxilico maleopinárico, resultando numa da fortificação da resina (HOVEY *et al.*, 1940; PAYNE, 1961).

A reação de Diels-Alder é exotérmica e com 5-10% de anidrido maleico que entra em ebulição aos 60ºC, a reação aos 150-200ºC é completa dentro de ½ hora. O ácido maleico reage igualmente rápido mas simultaneamente dehidrata para uma estrutura de anidrido. Com o ácido fumárico, a reação de Diels-Alder prossegue à mesma velocidade, apesar do seu elevado ponto de ebulição (300ºC) (HALBROOK *et al.*, 1958).

Para a estabilização da resina à oxidação, o ácido abiético é o único ácido resínico que absorve oxigénio, pelo que fica mais descolorada, o que na gema de pinheiro manso não é tão acentuado, uma vez que o ácido levopinárico tem a capacidade de manter a sua cor clara, já que não captura oxigénio.

Para que seja evitado este fenómeno no Pez, há um número de patentes para o Pez desproporcionado e para o tratamento térmico com recurso a catalisadores adequados - como o enxofre ou oxiácidos de enxofre ou seus sais - em combinação com antioxidantes. Os antioxidantes adequados e usualmente utilizados são diarilaminas e fenil-β-nafetilamina, benzofenol (BARTHEL *et al.*, 1954; DRESHFIELD, 1942; STRAZDINS,1954,1957).

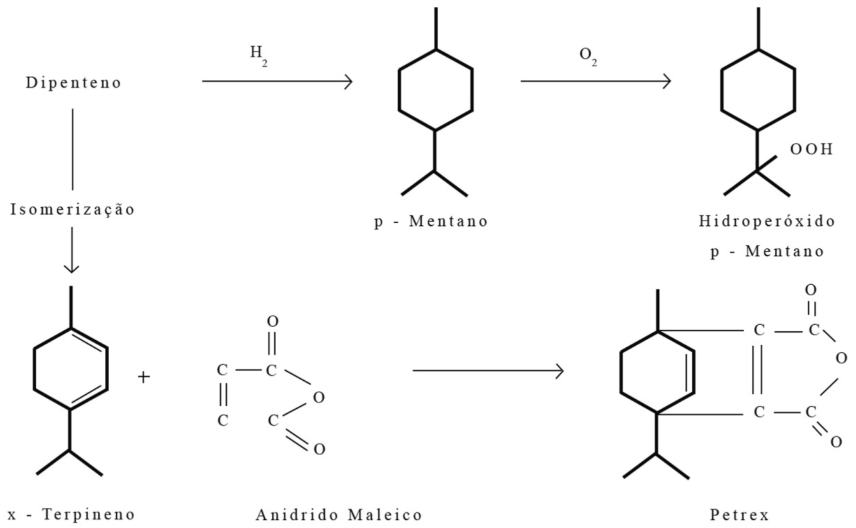

Figura 3 *– Sequência reacional para a obtenção de "petrex" e de hidroperóxido de p-mentano a partir do dipenteno*

Nota final

Este artigo de revisão restrito a dois dos constituintes da resina de pinheiro manso permite constatar que não há trabalhos recentes sobre estes dois compostos, o que indica que estes têm sido estudados algum tempo, não havendo nada de novo na sua aplicação, e há um desinteresse nesta matéria-prima, já que existe uma matéria-prima alternativa competitiva – O Petróleo. Contudo, aquela matéria-prima (resina de pinheiro manso) poderá ser diferenciada por ser um produto natural renovável.

Assim, pelo que foi demonstrado, cremos que esta árvore possui características que julgamos importantes a explorar. Reconhece-se a necessidade de incentivar ações conducentes à sua expansão, com "indivíduos" selecionados para dar fruto (pinhão) com as características conhecidas e a que possa associar-se a produção de resina (com altos teores em ácido levopimárico e com uma fração volátil quase exclusivamente constituída por limoneno, produto de grande interesse químico, como já foi evidenciado).

Referências bibliográficas

ANJOS, O., GARISO, L., MACHADO, H., PESTANA, M., 2009. *Pine oil potential as agent to preserve Pinus pinaster wood*. Forestry, Wildlife and Wood Sciences for Society Development. April 16-18, Prague, Czech Republic.

BARTHEL, J., HASTINGS, R., 1954. U.S. Patent 2,680,694 e 2,471,714.

CESE, 1996. Conselho Ensino Superior Empresa, *O sector florestal Português,* Povoa do Varzim, 4-5 Outubro.

CARVALHEIRO, B.G., 1986. *Química dos ácidos resínicos*. LNETI, Lisboa, pp. 2-16.

CARVALHO, J.S., 1986. Potencialidades químico-tecnológicas da *P. radiata* em Portugal, *1ºCongresso Florestal Nacional*, Fundação Calouste Gulbenkian, Lisboa, 2- 6 Dezembro.

DEFER, J., 1978. *Perfumer & Flavorist* **3**: 45.

DRESHFIELD, A., 1942. U.S Patent 2,294,723 e 2,294,929.

DUPONT, G., 1926. Les Essences de Térébenthine, 3ªPartie, *Nasson & Cª - Gautheir Villards &Cª*, Paris, pp. 267-322.

FIGUEIREDO, A.C., PEDRO, L.G., BARROSO, J.G., TRINDADE, H., SANCHES, J., OLIVEIRA, C., CORREIA, M., 2014. *Pinus pinaster Aiton e Pinus pinea L.*, AGROTEC/Agosto 2014, pp.14-18 (http://cbv.fc.ul.pt/Agrotec_12_14_Pinus.pdf, consultado em 20 de Julho de 2016).

GIGANTE, B., CURTO, M.J.M., LOBO, A.M., PRABHAKAR, S., 1987. O pinheiro: Fonte renovável de matérias-primas para a indústria química. 1. Os ácidos resínicos em química fina. *Boletim do Instituto dos Produtos Florestais - Resinosos,* Janeiro/56/XV, pp. 8-10.

HALBROOK, J., LAWRENCE, R., 1958. *Industrial and Engineering Chemical* **50**: 321.

HARRIS, G., SANDERSON, T., 1948. *Journal of the American Chemical Society* **70**: 334.

HOVEY, A., HODGINS, T., 1940. *Industrial and Engineering Chemical* **32**: 272.

KARR, L., COAT, J., 1988. *Journal of Pesticide Science* **13**: 287.7.

LOMBARD, R., 1924. *Produits Resineux*, Dunod, Paris, pp. 66-72.

LOURENÇO, J., ALMEIDA, J., 1980. *Boletim do Instituto dos Produtos Florestais - Resinosos* **30**(5): 5-12.

PAYNE, H., 1961. *Organic Coating Technology*, Vol I, John Wiley and Sons, pp 156-161.

PESTANA, M., 2011. The insecticides obtained from turpentine, *Silva Lusitana nº especial* pp. 127-133.

RUCKEL, E., ARLT Jr., H., 1984. Polyterpene resins in 1983 hot melt 1. *Naval Stores Review*, **94**(1): 6-10.

RUCKEL, E., ARLT Jr., H., 1984a. Polyterpene resins in 1983 hot melt 2. *Naval Stores Review*, **94**(2): 4-8.

SAMPAIO, J.T., 1988. Portuguese gum rosin derivates – presente & future, *Naval Stores Review* **98**(6): 6-8.

SEDEL'NIVOK, A., TIKHONOVA, T., POLYAKOVA, N., LARIONOV V., 1985. Self-cleaning apparatus and method for thick slurry pressure control. *Gidroliznaya I Lesokhimicheskaya Promyshlennost* **4**(12): 12-14.

SILVA, M., 1991, *Aguarrás - Aplicações Industriais*, INETI, Lisboa, nº 2.

SKOLNIK, H., ENOS, H., GARDNER Jr, C., 1963, Literature of chemical technology, *Forest Products Research Society*, National Meeting of New Orleans.

STAROSTINA, E., NESTEROVA, E., SEDEL'NIKOV, A., 1987. Ligned procuding from lignocellulosic Biomass, *A Gidroliznaya i Lesokhimicheskaya Promyshlennost* **1**(26): 14-15.

STRAZDINS, E., 1954. Canadian Patent 508,321.

STRAZDINS, E., HASTINGS, R., 1957. U. S. Patent 2,776,221.

TAYLOR, W. I., CHANT, B., LOVEREN G., 1981. Kirk-Othmer Enciclopedia of Chemical Technology, 3º ed., vol 13, *John Wiley & Sons Inc.*, New York, pp. 575-596.

TAYLOR, W. I., CHANT, B., LOVEREN G., 1983. Kirk-Othmer Enciclopedia of Chemical Technology, 3º ed., vol 22, *John Wiley & Sons Inc.*, New York, pp. 709-756.

VEZES, M., DUPONT, G., 1924. *Resines et terebentines.* Librairie J. B. Biailiere et Fils, Paris, pp. 66-72.

ZINKEL, D., RUSSELL, J., 1989. Naval Stores, *Pulp Chemical Association*, New York, pp. 477-572.

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A Unified Theory for Self-Thinned Pure Stands A Synoptic Presentation

Luís Soares Barreto

Abstract. The author presents a synopsis of his unified theory for self-thinned pure stands that he is developing since the 80's. The hypothetic-deductive theory is explained as a triplet $T=\langle D, A, L \rangle$. In set *D,* basically, he says what is the object of the quest, establishes the object-concept relation, and introduces definitions. Set *A* embraces the minimum group of statements about the object of study, required to get more insight about it. Fundamentally, set *L* says how self-thinned pure stands are dynamically self-organized. It contains the corollaries, and laws deduced from *D,* and *A.* The author elaborates an epistemological analysis of his theory, and exhibits an application.
Key words: Self-thinned pure stands, unified theory, epistemological analysis

Sinopse de uma teoria unificada para os povoamentos puros auto-desbastados

Sumário. O autor apresenta uma sinopse da sua teoria unificada para os povoamentos puros auto-desbastados, em que vem trabalhando desde os anos oitenta. A teoria hipotética-dedutiva é apresentada como um tripleto $T=\langle D, A, L \rangle$. O conjunto *D* define o propósito da inquirição, estabelece as relações objeto-conceito e introduz definições. O conjunto *A* encerra as assunções indispensáveis, acerca do objeto de estudo, para se poder obter mais conhecimento a seu respeito. O conjunto *L* descreve como os povoamentos puros auto-desbastados estão dinamicamente auto-organizados. Contem leis e corolários deduzidas a partir de *D* e *A.* O autor apresenta uma análise epistemológica da sua teoria e apresenta um exemplo de aplicação.
Palavras-chave: análise epistemológica; povoamentos puros auto-desbastados; teoria unificada

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Synopse d'une théorie unifiée pour les peuplements purs et auto éclaircis

Résumé. L'auteur présente une synopse de sa théorie unifiée pour les peuplements purs et auto éclaircis qu'il a commencé à développer dans les années 80. Sa théorie hypothético-déductive peut être représenté par le triplés $T=\langle D, A, L \rangle$. L'ensemble *D* défini l'objecte de l'enquête, établi les relations objecte-concept et présente les définitions. L'ensemble *A* contient les conjectures sur l'objecte indispensables pour développer la théorie. Les lois de la théorie et ses corollaires sont présentées dans l'ensemble *L*. Une application de la théorie et son analyse épistémologique sont aussi présentées.

Mots clés: Analyse epistémologique, peuplements pures auto éclaircis, théorie unifiée

Introduction

It is admitted that it were attempts to solve many practical problems in agriculture, fisheries, and forestry that gave origin to many of the central ideas, concepts and methods, in ecology (KINGSLAND, 1985: 23). I must confess that the results here presented are rooted in practical problems.

In Portugal, due to the fact that forest holdings are very small in area, the extension of managed forests is very restricted. In this situation, the use of classical forest yield tables is of very limited utility. The prediction of the growth of forest stands, in Portugal, is mainly a matter of projecting pure self-thinned stands, showing variable density. My research, whose results are here presented, at first, was mainly an answer to this problem, as we faced it in Portugal. Furthermore, I admitted that the predictions of forest stand growth, managed stands included, is a problem still waiting for a better solution in forest science. I also accept that the better is my understanding of natural stand dynamics the better will be my chances to improve my predictions of the growth of managed stands, and also the practice of forest management. In fact, my theory for self-thinned stands let me already, successfully, approached the effects of thinning (BARRETO, 2001c).

Therefore, the scope of this paper is to present a synthesis of the results I achieved about the structure, dynamics, and allied properties of both self-thinned even-aged pure stands (SEPS), and self-thinned uneven-aged pure stands (SUPS). Most of them had been disseminated through three short books in this line of research (BARRETO, 1987, 1994a, 1995a) and several research papers that will be referred in due time.

To avoid misinterpretations and to provide an adequate context for the results here presented, a relevant issue must be clarified: the one related to the time frame and scale (ALLEN and STARR, 1982). My time frame is the natural longevity of a cohort of a given tree species, and the focus of my research is the tree population of self-thinned pure stands (SPS).

It is my understanding that the results here presented, as a conceptual framework, can be generalized to other plant populations. SPS are particularly suitable to study the dynamics of plant populations. Trees and their components are easily individualized and measurable. They also evince a conspicuous picture of self-thinning, due to their fierce competition, and longevity (ZEIDE, 1991:518). Briefly, this is a synopsis of a theoretical inquiry on the process of self-thinning, and growth of a tree population, that I started in the eighties.

The very basic assumption of the inquiry summarized in this paper is the following one: *although, in nature, SPS are stochastic systems, the analysis of a deterministic archetype can bring valuable knowledge, and make a bridge for the stochastic approach,* as I already illustrated and accomplished in BARRETO (2006). For my conception of the growth of SEPS see BARRETO (1989a: 241; 2002).

Thus, a theory for SPS is situated in the realm of ecology. This science is considered immature, with a very incipient theoretical structure by some authors (e.g., ROUGHGARDEN, 1998: xi). Ecology, as social sciences, has a poor nomological structure. It is rich on data, and interpretative hypotheses, but evinces a very scarce number of laws or regularities (MAHNER and BUNGE, 1997: Chap. 5). SHRADER-FRECHETTE and E.D. McCOY (1995: 8) characterizes ecology as a science of case studies. It is admitted that the complexity and the diversity of systems studied by ecology justify this situation (McINTOSH, 1985: 247).

Although the previous allegations have factual support, it must be remembered that the inquiry of ecology approaches natural systems at different levels of hierarchy. At the level of population ecology, it is already possible to attempt a hypothetic-deductive approach with variable depth, and breath (BARRETO, 1990b; TURCHIN, 2003). Turchin, in the final section of his book, has no doubts in defending, in a vivid manner, the scientific maturity of population ecology.

The macroscopic architecture of my theory is illustrated in Figure 1, and the inquiring strategy in Figure 2.

This paper is a revised version of BARRETO (2003b).

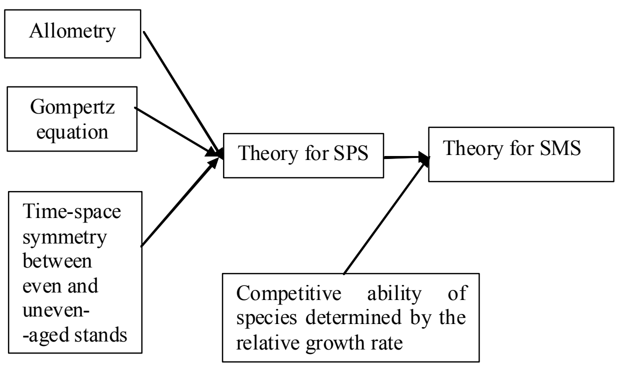

Figure 1 *- Basic diagram of the broad conceptual structure of my theory for self-thinned pure stands (SPS), and self-thinned mixed stands (SMS)*

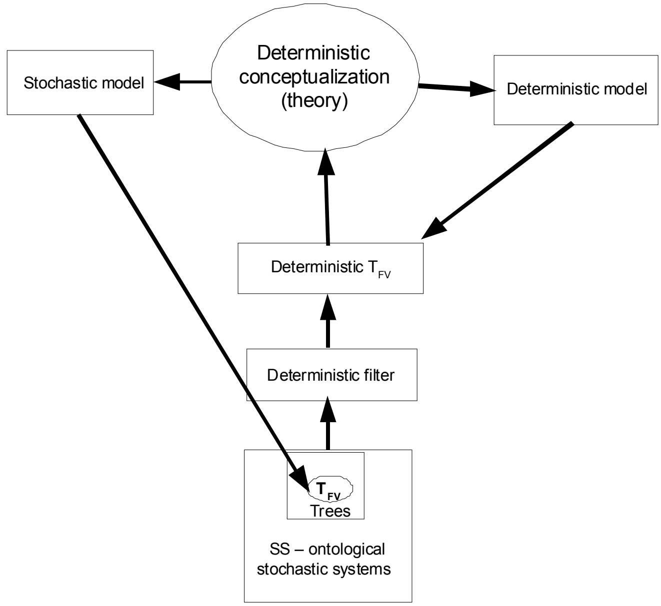

Figure 2 *- Figurative description of the analytical scheme.* T_{FV} *represents the properties of the tree population described by the language of forest variables. Arrows pointing up represents abstraction, arrows pointing down indicate subsumption. SS= self-thinned stands*

A Framework for Analysis

Let me present a conceptualization of SPS that will endorse an easier subsequent analysis (MAHNER and BUNGE, 1997: section 1.7).

A SPS is a system *s* with components (*C*), located in an environment (*E*). The several components of *s* are interrelated among them, this is, *s* has an internal structure (S_I), and with the environment (external structure, S_E).

As I am working at population level, not ecosystem level, my interest is focused in one component: the trees and their structure *S* (=$S_I \cup S_E$).

The relevant quantitative properties of *C* are the number of trees, their size, and the related derived properties at stand level, because I am interested in self-thinning, tree and stand growth.

The scope of my quest is to clarify *S*, with the main focus in S_I, as I assume *E* invariant during the stand life, but not the same for all *s*.

The elucidation of *S* is accomplished by establishing nomological relationships, or laws, among the quantitative properties of *s*, here also named forest variables. These laws are dominantly mathematical relationships. I want to describe the ontological system *s* with a conceptual system or theory $\mathcal{T}$.

Most knowledge about self-thinning and forest growth is translated in a collection of models. My aim is to create a coherently unified set of models.

Now, I introduce my high level assumptions about system *s*:

1. It is a complex ontological entity, but there is simplicity that emerges from this intricacy. This situation allows the description of SPS by simple equations (COHEN and STEWART, 1994: 411).

2. The growth of individuals obeys to eco-physiological, chemical and physical constrictions.

3. The occupancy of the space by the population of trees of a SPS abides physical constraints.

In a broader perspective, my theory converges to the main conceptions of James H. Brow, Brian J. Enquist, and Geoffrey B. West that are explained, and illustrated in BROWN and WEST (2000).

$\mathcal{T}$ can symbolically represent my hypothetic-deductive theory, T=⟨D, A, L⟩.

Set D: it contains definitions, forest variables, and conventions, mainly the propositions that establish the object-concept relation. Basically, it states the object of the enquiry, and introduces its descriptive and operational conceptualisation.

Set A: it includes the basic assumptions. They behave as axioms but they are not postulates in the classical sense, because some of them can be proved. This set encompasses the minimum group of conjectures, or hypotheses, I must formulate about system *s*, in order to get more insight about it.

Set L: it embraces the corollaries and theorems or laws, about *S*, deduced from *D*, and *A*.

I consider the elements of *L* (except corollaries) law statements because: a) they apply to all tree species and SPS; b) they are integrated in a hypothetic-deductive system; c) they are being satisfactorily confirmed (MAHNER and BUNGE, 1997, Definition 3.9). *A* and *L* can be seen as the syntactic of $\mathcal{T}$.

$\mathcal{T}$ is logically structured, avoids an excess of formalism not accessible to everyone, and allows an ordered, systematic, and controllable rationalization of the theory for system *s*.

In this summarized presentation, I will not repeat the proofs I already introduced elsewhere, but I will indicate the pertinent references.

The admitted units are: age: year; stand area: hectare; height, tree spacing: meter; diameter: centimetre; basal area, area per tree, area per module: m^2; volume: m^3; tree biomasses: kg of dry matter; stand biomasses; ton of dry matter. The subsequent elaborations also assume: a) the number of trees is dimensionless; b) the rigid rescaling of body volume to body mass is possible (SCHNEIDER, 1994: 313).

A Theory for SPS

Set D

The set *D* encompasses the following:

D1. Forest variables are represented by $y_{ijt.}$ The first subscript, *i* refer to the power of the linear dimension associated to the variable, *j* identifies the variable, *t*, as usual refer to the age in years. The variables considered are described in Table 1.

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				

***Table 1** - Continuation*

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

D2. After age t_0 the trees are mainly subjected to intraspecific competition, both in SEPS and SUPS. At this age, I write y_{ij0}.

D3. y_{ijf} is the final or asymptotic value of the variable

D4. $R_i = y_{ij0} / y_{ijf}$

D5. $c>0$ and $R_i>0$ are biological parameters that mirror the life-history strategy of the tree species

D6. $RGR_j=1/y_{ijt}\, y_{ijt}/dt$ (relative growth rate; relative mortality rate for y_{-21t})

D7. Mean annual increment (MAI) is y_{ijt}/t

D8. Current annual increment (CAI)=$y_{ijt+1} - y_{ijt}$

D9. $\mathcal{T}Y_j$=stand volume or biomass of self-thinning plus stand volume or biomass at age w. j=e for SEPS; j=u for SUPS, also called gross yield.

D10. *Ne*= number of trees, at age t_0, per module, in SEPS.

D11. *Ae*= area per module, in SEPS.

D12. *Me*= number of modules per hectare, in SEPS.

D13. *Nu*= number of trees, in SUPS.

D14. *Au*= area per module, in SUPS.

D15. *Mu*= number of modules per hectare, in SUPS.

D16. The relative spacing *rs*, is defined $rs=s_t/y_{1jt}$, s_t= tree spacing

D17. The form factor is defined as $F_f=y_{31t}/(y_{22t}\, y_{12t})$.

D18. The Shannon-Wiener index is used as a measure of the structural entropy of SPS.

Set A

A1. Self-thinning is a neutral thinning (BARRETO, 1994d).

A2. Environment affects the size, form, and spacing of trees (site quality). As reference value, tree spacing at age 40 years s_{40} is assumed as a measure of both this influence and the level of use of the local resources, by the trees. I call this variable *index of performance* (BARRETO, 1995b).

A3. In SEPS life, three phases can be depicted. Phase I: from age 0 to age t_0, interspecific competition is dominant. Phase II: from age t_0 till the beginning of the asymptotic phase (negligible growth), intraspecific competition is dominant; Phase III: when the stand growth is nullified by aging. *$\mathcal{T}$ is specifically devoted to phase II.*

A4. Trees have allometric growth.

A5. Forest variables follow the Gompertz equation (BARRETO, 1993a; MEDAWAR, 1940), thus the following relationship is verified:

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

A6. c and R_i, are constant for a given species (consistent with D5).

A7. There is time-space symmetry between SEPS and SUPS. The factual meaning of this assertion is the following one: the temporal successions of trees that occupy one area unit, in a SEPS, from t_0 to w, coexist in a SUPS with u area units ($u=w-t_0$), plus regeneration and recruitment (trees with age$<t_0$).

A8. In SUPS, trees younger then t_0 live under the cover of older trees (from D2).

A9. For a given SUPS, there is a stable age structure.

Set L

Corollaries

C1. If $R_i>1$ y_{ijt} decreases with age.

C2. If $R_i=1$ y_{ijt} is constant

C3. If $R_i<1$ y_{ijt} increases with age.

Theorems or laws:

L1. SPS are self-similar entities, formed by identical modules with $y_{-21f}=1$ (BARRETO, 1995b).

L2. The allometric relationship between variable y_{ajt}, and y_{bjt} is given by

$$y_{ajt}=a_{ab}y_{bjt}^m \quad (2)$$

$m=a/b$ (dimensional analysis, e.g., BARRETO, 1989a: 237-238); a_{ab} is affected by the index of performance.

[The 3/2 power law is a particular case of this equation, and applies only to the volume or biomass of the tree stem (BARRETO, 1994b, 1995b)].

L3. The following relationship holds (A5, L2):

$$R_a = R_b^m \quad (3)$$

L4. The following relationship is verified (L3):

$$RGR_a = m\ RGR_b \quad (4)$$

L5. Variables y_{0jt} are constant (BARRETO, 1990b).

L6. The equation for tree volume (v) is (L2):

$$v=a\ x^3 \quad (5)$$

where x is the tree dbh or height, and a is a constant that depends on the index of performance.

L7. In all SEPS of a given species, the following relationship holds (A5):

$$y_{ijt}/\ y_{ijt'} = constant \qquad t \neq t',\ i \neq 0 \quad (6)$$

L.8 Tree growth abides the allometric model of geometric similitude (L2; NIKLAS, 1994: 165).

L9. The age of MCI of variable y_{ij} occurs at age T_c, when the following is verified (BARRETO, 1990b):

$$R_i^{exp(-c(T_c-t_0))} = e^{-1} \quad (7)$$

L10. At age T_c, the following is verified (L9):

$$RGR_i = c \quad (8)$$

L11. The maximum CAI of variable y_{ij} ($MCAI_{ij}$) is given by (L9, L10):

$$MCAI_{ij} = y_{ijf}\ e^{-1}\ c \quad (9)$$

L12. The maximum MAI of variable y_{ij} occurs at age T_m, that satisfies: (BARRETO, 1990b):

$$T_m = RGR_i^{-1} \quad (10)$$

L13. $$TY_e = ln\ (R_{-2})\ y_{1jf}\ c \int_{t_0}^{w} C R_{-2}^{-1/2C} dt\ +\ y_{1jf}\ R_{-2}^{-1/2F} \quad (11)$$

$$C = exp(-c(t-t_0)) \quad (12)$$

$$F = exp(-c(w-t_0)) \quad (13)$$

j=4 (BARRETO, 1994c)

Eq. (11) can be extended to root, above-ground, total biomasses per area unit, but in the power of $R_{-2,}$ the constant is less then ½.

L14. $Ne=R_{-2}$ (14)

(BARRETO, 1995b)

L15. $Ae=s_{40}^2\ Ne\ R_{-2}{}^{C_{40}^{-1}}$ (15)

$C_{40}=exp(-c(40-t_0))$ (16)

(BARRETO, 1995b)

L16. $Me=Ne^{-1}\ s_{40}^{-2}\ 10^4\ R_{-2}{}^D$ (17)

$D=1-C_{40}$ (18)

(BARRETO, 1995b)

L17. Consider two distinct variables y_{ajt}, and y_{bjt}, measured at two different ages $t>t'$, then the following relationship holds: $y_{ajt'} = y_{ajt}\,(y_{bjt'}/y_{bjt})^m$, m=a/b. After you measure a SEPS, latter you only have to count the number of trees to obtain its structure (BARRETO, 2001c).

L18. $y_{-210}=10^4\ R_{-2}{}^D\ s_{40}^2$ per ha (19)

(BARRETO, 1995b)

L19.From A6, several of the regularities, depicted for SEPS, are applied not in time, but in space, in the SUPS. Now the reference is the set of trees with the same age. These regularities are easily identified (BARRETO, 1989b, 1990a, 1995a. See Appendix).

L20. $Au=(w-t_0+1)Ae$ (20)

(BARRETO, 1995b)

L21. $$Nu=\sum_{t_0}^{w} Ne^{exp(-c(t-t_0))}$$ (21)

(BARRETO, 1995b)

L22. $Mu=(w-t_0+1)^{-1}Me$ (22)

(BARRETO, 1995b)

L23. The gross yield of a SUPS per area unit, per year, is given by:

$TY_u=TY_e/(w-t_0)$ (23)

L24. *rs* is constant (BARRETO,1990b).

L25. F_f is constant (BARRETO, 1990b).

L26. During the of a SEPS, for each age, using the frequencies, standing volume or biomass, total standing biomass, of the dbh classes, the entropy is constant, and equal to entropy of self-thinned trees. This property is verified in the space continuum in SUPS. From A1, A7. See Appendix.

L27. During the growth of the tree, its architecture abides several relationships. For a complete illustrative cases see BARRETO (1994e: 240-241; 1999:4; 2000:83-84).

Application

In Table 2, I characterize the SEPS and SUPS of *Pinus pinaster*, *Fraxinus excelsior*, and *Abies grandis*, three species that have conspicuously different life-history strategies (BARRETO, 2003b, 2008).

Table 2 *- The characterization of trees and SPS of Pinus pinaster (maritime pine), Fraxinus excelsior (ash), Abies grandis (white fir);* t_0*=10 years. Ne, Nu in trees/module; Ae, Au in* m^2*/module; Me, Mu in modules/ha;* y_{-21}*,* y_{-210} *in trees/ha. V=variables; LHS=life-history strategy (BARRETO, 2003a); GI=growth index; RI=regeneration index; SI=survival index (BARRETO, 2003b)*

V	*Pinus pinaster*	*Fraxinus excelsior*	*Abies grandis*
c	0.050	0.038	0.055
w	100	300	550
LHS	r-3	r↔K	K-3
GI	0.743	6.695	217.889
RI	0.138	0.001	0.000
SI	0.862	0.999	1.000
R_{-2}	6.018	87.767	370.685
R_1	0.40764	0.10674	0.05194
T_c	8	31	30
R_2	0.16617	0.01139	0.00270
T_c	21	49	42
R_3	0.06774	0.00122	0.00014
T_c	30	60	50
Ne	6	87	370
Ae	1.493 s_{40}^2	4.183 s_{40}^2	3.107 s_{40}^2
Me	6697.7 s_{40}^{-2}	2390.8 s_{40}^{-2}	3210.9 s_{40}^{-2}
y_{-210}	40320 s_{40}^{-2}	209805 s_{40}^{-2}	1190222 s_{40}^{-2}
Nu	154	1102	2156
Au	135.868 s_{40}^2	2904.183 s_{40}^2	1678.860 s_{40}^2
Mu	73.601 s_{40}^{-2}	8.243 s_{40}^{-2}	5.940 s_{40}^{-2}
y_{-21}	11346 s_{40}^{-2}	9091 s_{40}^{-2}	12810 s_{40}^{-2}

In Figure 3, I present the patterns of growth for variables y_{1jt}, of the same species. For the purpose of illustration, I used the standing volume of the stem (m³/ha). The use of the logistic equation is not able to depict these patterns.

Let me quote MAY (1981: 7) about the logistic equation: "It must be emphasized that the specific form of eq. (2.3) is not to be taken seriously". Besides empirical studies, it can be shown that the Gompertz equation is a true mechanistic, or explanatory model for biological growth (BARRETO, 1993a; MEDAWAR, 1940). Many authors verified that the Gompertz equation is the most adequate to model biological growth (CAUSTION, and VENUS, My monograph dedicated to *Pinus pinea* illustrates comprehensively an application of τ (BARRETO, 2000).

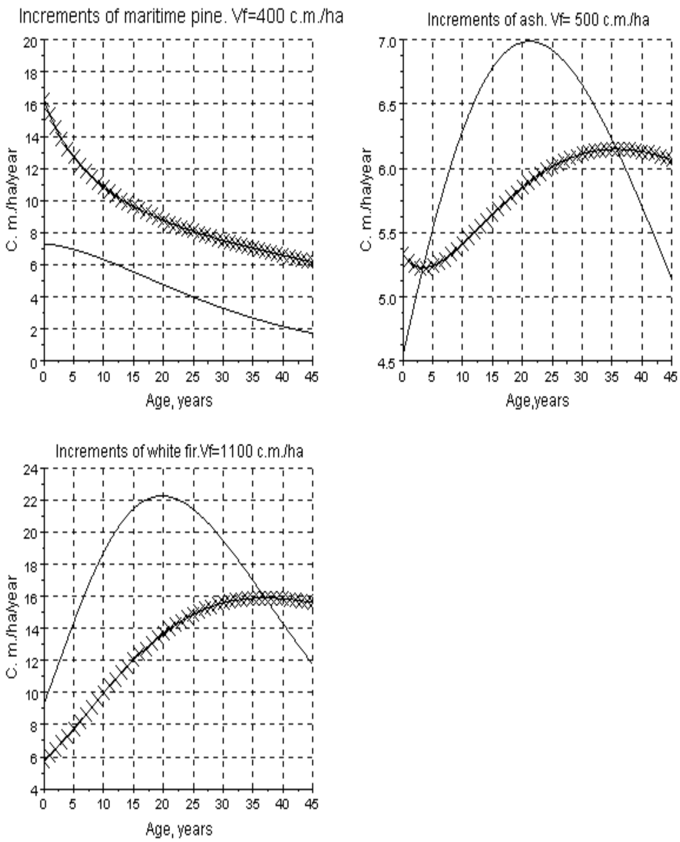

Figure 3 - *Mean annual increment (crosses) and current annual increment of the standing volume of stem in three trees with different life-history strategies. Vf=final or asymptotic standing volume*

I already established several program listings, and disseminated several Visual Basic 6 applications, to simulate SPS of several European and North America tree species (freeware) (BARRETO, 1991, 1993b,c, 1994c).

Evaluation

Before I state my appraisal of the theory, let me clarify a methodological issue. The theory does not endorse the *received view* from neopositivism. It is inspired in the conception of *scientific realism* (LUCENA, 1998; MAHNER and BUNGE, 1997: section 3.5; table 9.1), although it does not follow its format in a strict way.

To evaluate the theory I just summarized, I use the following criteria (MAHNER and BUNGE, 1997: 131-133): empirical evidence; internal consistency; external consistency; unifying power; fecundity.

Empirical evidence

- I was able to simulate several published yield tables for a variety of species.
- The theory is easily testable, given its high level of integration. L7 is a crucial proposition. Its invalidation will affect the theory in large extension.
- My theory supported the stochastic simulation of SEPS and SUPS. The values of the power of the 3/2 power law generated by my stochastic simulations agree with the empirical evidence available (BARRETO, 2002).

Using simulator PINASTER, grounded in my theory, for *Pinus pinaster,* the power of density in the allometric equations for tree above ground biomass, and total tree biomass is, respectively, -1.34, -1.36 (BARRETO, 1994b: 23). These two figures have empirical and conceptual support (ENQUIST, WEST and BROWN, 2000: 185-186), and are closer to -4/3, than to -3/2. The theoretical correct figure is 2.7/-2. Also, this scaling implies $y_{2.7} \propto y_{11}^{2.7}$. This equation can be obtained from engineering first principles, as pointed out by NIKLAS, and ENQUIST (2001: 2926), and represents a physical constraint to tree growth.

Internal consistency

- The way I deduced my theory confers to it a high level of internal consistency.
- My theory is highly integrated. It provides a unified and coherent description of SPS.
- My theory is enough integrated to allow alternative formulations of set *A*

External consistency

- All my equations are dimensionally homogeneous.
- The patterns of growth generated by my models are consistent with the life-history strategies of the species (BARRETO, 2008, 2009).
- My results agree with conceptualizations of the real world established by several authors (see my high level assumptions, upper presented).
- My results do not contend, as far as I can verify, with any main ecological conceptualization.

Unifying power

- My theory for SPS let me establish a derived theory for mixed stands, both even and uneven-aged. I already distributed several simulators for mixed even-aged stands (VB 6 applications; freeware).
- It is only necessary to have a time series of one variable in a SEPS, $y_{ij,}$ to obtain *c*, and *Ri*. From this two parameters, the rest of the dynamics of the species can be obtained, as the body of an extinguished species is reconstructed from only few bones that were found. Probably, in nature, at the macroscopic level, there are patterns of regularities that permeate all biosystems.
- For the first time we have a unified theory for pure and mixed stands, both even and uneven-aged.

Fecundity

- My theory allowed me to establish growth, regeneration, and survival indices with real biological and ecological meaning (BARRETO, 2003a,b).
- My theory permitted me to clarify the effects of thinning in a conceptualized manner, coherent with other fields of biology, and ecology. *The effects of thinning abide the law of diminishing returns* (BARRETO, 2001c).
- My theory allowed me to conceptualize tree competition, and establish models for plant competition (BARRETO, 1997, 2001a, b), also applicable to other organisms (BARRETO, 2005a,b).
- My theory allowed me to establish the fractal geometry of trees, SPS, and some scaling factors for transformations within the hierarchical levels I approached (trees, and SEPS). (BARRETO, 1995b).
- My theory let me clarify the abiding of the Kleiber's law by the net production year^{-1} of plants (BARRETO, for publication).
- My theory let me show the time self-similarity of biological growth (BARRETO, 2004b, 2005b).
- My theory let me use restrict information of stands of *Pinus pinaster* and *Pinus pinea* to establish a complete portrait of the structure, dynamics and closed biogeoche-mical of their stands (BARRETO, 2000, 2004a). The existence of a unified theory let corroborate the following statement of Richard Feynman: "Nature uses only the longest threads to wave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry" (FEYNMAN, 1967: 34).

Final Comments

It is required that I justify my very basic assumption stated in the Introduction. My rationalization is as follows:

a) If everything is explained only by exogenous induced variation, the situation is not lawful or nomological, and there is no place for science. The world it is not deterministic in Laplace's strict sense, but in a comprehensive sense of nomological. Besides this ontological assumption, the existence of science requires an epistemological one: the natural order is accessible to human knowledge.

b) The problem in ecology is the specification of the significant parameters that must be measured, are relevant for the state of the system, and thus will allow the emergence of a lawful situation. Here, this problem has a much more difficult solution than in physics.

c) In an ecological system, what is admitted to be an exogenous induced variation is affected by the level of available knowledge, and it has implicit (as a necessary reference) a mechanistic conceptualization (with variable degree of refinement) of it, even if not clearly stated and described. The choice of what to measure is underpinned by an initial conceptual model of the system we want to study.

My understanding is that my theory has high probabilities to correspond in a minimum acceptable extension to the deterministic conceptualization of trees and SPS. In reality, SPS are stochastic, and richer materializations of this deterministic description (BARRETO, 2006).

Ecological sound forest management requires a more broad knowledge of forest ecosystems than the management concentrated in timber production (e.g., PUETTMAN, COATES, CHRISTIAN MESSIER, 2009: 119, 143, 144) but it can not overcome the necessity of a correct theory for plant populations, particularly for trees, the dominant populations in forests.

Ecology can only respond satisfactorily to the exigencies imposed by the sustainable management of natural resources and environmental problems if equipped with a sound theoretical and encompassing structure. This assertion is not original, but it must not be forgotten.

Here, I conclude the summarized description of the solution I invented to solve my seminal problem.

An actualized, and more embracing theory for forests can be found in BARRETO (2011)-

References

ALLEN, T.F.H., STARR, T.B., 1982. *Hierarchy. Perspectives for Ecological Complexity.* The University of Chicago Press, Chicago.

BARRETO, L.S., 1987. *Um Novo Método para a Elaboração de Tabelas de Produção. Aplicação ao Pinhal.* Serviço Nacional de Parques, Reservas e Conservação da Natureza, Lisboa.

BARRETO, L.S., 1989a. The 3/2 power law: a comment on the specific constancy of K. *Ecoll. Modelling* **45**: 237-242.

BARRETO, L.S., 1989b. *The Structure and Yield of Uneven-aged PURE stands. A theoretical* approach. Centro de Estudos Florestais, INIC, Lisboa.

BARRETO, L.S., 1990a. *Two Species Even-aged Self-thinned Stands. A Simulation Approach.* Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 1990b. S*elf-thinned Pure Stands. A Unified Approach.* Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 1991. SPESS - A simulator for pure even_aged self-thinned stands. *Ecoll. Modelling,* **54**: 127-132.

BARRETO, L.S., 1993a. *An Alternative Proof for Model KHABA.* Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 1993b. UMBRELLA – a first simulator for self-thinned even-aged puré stands of umbrella pine. *Silva Lusitana* **1**(2): 157-162.

BARRETO, L.S., 1993c. KHABARD – a simulator for European hardwood forests. *Silva Lusitana* **1**(2): 163-168

BARRETO, L.S., 1994a. *Alto Fuste Regular. Instrumentos para a sua Gestão.* Publicações Ciência e Vida, Lda, Lisboa.

BARRETO, L.S., 1994b. The clarification of the 3/2 power law using simulators SANDRIS and PINASTER. *Silva Lusitana* **2**(1): 17-30.

BARRETO, L.S., 1994c. KHABASOFT – a simulator for European forests of softwood species. *Silva Lusitana* **2**(1): 31-39.

BARRETO, L.S., 1994d. The clarification of self-thinning and thinning. A simulation approach. *Silva Lusitana* **2**(2): 233-238.

BARRETO, L.S., 1994e. The dynamics of the biomssof maritime pine trees and stands. *Silva Lusitana* **2**(2): 239-346.

BARRETO, L.S., 1995a. *Povoamentos Jardinados. Instrumentos para a sua Gestão.* Publicações Ciência e Vida, Lda, Lisboa.

BARRETO, L.S., 1995b. The fractal nature of the geometry of even-aged self-thinned stands. *Silva Lusitana* **3**(1): 37-52. .

BARRETO, L.S., 1999. *Model CORSO and the Dynamics of the Biomass of Trees and Stands of Corsican Pine.* Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2011. *From Trees to Forests. A Unified Theory.* E-Book, Costa da Caparica

BARRETO, L.S., 2000. *Pinhais Mansos. Ecologia e Gestão.* Estação Florestal Nacional, Lisboa.

BARRETO, L.S., 2001a. *O Modelo BACO3 para a Competição entre Plantas.* Research Paper SB-02/01. Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2001b. *SB-BACO4. A Gompertzian Discrete Model for Tree Competition.* Research Paper SB-03/01. Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2001c. Method SB-BARTHIN to Evaluate the Effects of Thinning. An Application to *Pinus pinaster* Ait. *Silva Lusitana* **9**(2): 205-216.

BARRETO, L.S., 2003a. *Software SB-CRESCER*. Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2003b. *A Unified Theory for Self-Thinned Pure Stands. A Synoptic Presentation.* Research Paper SB-03/03, Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2004a. *Pinhais Bravos. Ecologia e Gestão.* Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa.

BARRETO, L.S., 2004b. SB-KHRONOSKHABA. A Gompertzian Model for the Seasonal Growth of Forest Trees and Stands. An Application to *Pinus pinaster* Ait.. Research Paper SB-05/04. Departamento de Engenharia Florestal, Instituto Superior de Agronomia.

BARRETO, L.S., 2005a. *Gause's Competition Experiments with Paramecium sps. Revisited.* Research Paper SB-01/05. Departamento de Engenharia Florestal, Instituto Superior de Agronomia. Revised version submitted to *Silva Lusitana* in September 2007.

BARRETO, L.S., 2005b. *Theoretical Ecology. A Unified Approach.* Author's edition. Costa de Caparica.

BARRETO, L.S., 2006. The Stochastic Dynamics of Self-Thinned Pure Stands. A Simulative Quest. *Silva Lusitana***14**(2): 227-238.

BARRETO, L.S., 2008. The Reconciliation of the r-K, and C-S-R Models for Life-History Strategies. *Silva Lusitana* **16**(1): 97-103.

BARRETO, L.S., 2009. *Growth, Regeneration, and Survival Indices for Tree Species. Silva Lusitana* **17**(1): 85-93.

BARRETO, L.S., for publication. *Plant Growth and Kleiber's Law. A Theoretical and Simulative Inquiry.* Submitted to *Silva Lusitana* in April 2009.

BROWN, J.H., WEST, G.B., 2000. *Scaling in Biology.* Santa Fe Institute Studies in the Science of Complexity, Oxford University Press, Oxford.

CAUTION, D.R., VENUS, J.C., 1981. *The Biometry of Plant Growth.* Edward Arnold, London.

COHEN, J., STEWART, I., 1994. *The Collapse of Chaos. Discovering Simplicity in a Complex World.* Penguin Books, London.

ENQUIST, B.J., WEST, G.B., BROWN, J.H., 2000. Quarter-Power Allometric Scaling in Vascular Plants: Functional Basis and Ecological Consequences. In J.H. Brown, and G.B. West, 2000. *Scaling in Biology.* Santa Fe Institute Studies in the Science of Complexity, Oxford University Press, Oxford. pp. 167-198.

FEYNMAN, R., 1967. *The Character of Physical Law.* The MIT Press, Massachusetts.

KARKACH, A.S., 2006. Trajectories and models of individual growth. *Demographic Research* **15**: 347-400.

KINGSLAND, S.E., 1985. *Modelling Nature. Episodes in the History of Population Ecology*. The University of Chicago Press, Chicago.

LUCENA, A.D, 1998. *Realismo Científico. Una Introducción al Debate Actual en la Filosofia da Ciencia.* Servicio de Publicaciones, Universidad de Málaga, Málaga.

MAHNER, M., BUNGE, M., 1997. *Foundations of Biophilosophy*. Springer, Berlin.

MAY, R.M., 1981. Models for single populations. In R.M. May, Ed., *Theoretical Ecology. Principles and Applications.* Blackwell Scientific Publications, Oxford. pp. 5-29.

MEDAWAR, P.B., 1940. Growth, growth energy, and ageing of the chicken's heart. *Proc. Roy. Soc. B*. **129**: 332-355, London. As mentioned in Zeide (1993).

McINTOSH, R.P., 1985. *The Background of Ecology. Concept and Theory.* Cambridge University Press, New York.

NIKLAS, K.J., 1994. *Plant Allometry. The Scaling of Form and Process.* The University of Chicago Press, Chicago.

NIKLAS K.J., ENQUIST, B.J., 2001. Invariant scaling relationships for interspecific plant biomass production rates and body size. *Proc Nat Acad Sci U S A* **98**: 2922-2927.

PUETTMAN, K.J., COATES, K.D., MESSIER, C., 2009. *A Critique to Silviculture. Managing for Complexity.* Island Press, Washington.

ROUGHGARDEN, J., 1998. *A Primer of Ecological Theory.* Prentice Hall, Upper Sadle River, NJ.

SCHNEIDER, D.C., 1994. *Quantitative Ecology. Spatial and Temporal Scaling.* Academic Press, San Diego.

SHRADER-FRECHETTE, K.S., 1995. *Method in Ecology. Strategies for Conservation.* Cambridge University Press, New York.

TURCHIN, P., 2003. *Complex Population Dynamics. A Theoretical/Empirical Synthesis.* Princeton University Press, Princeton.

ZEIDE, B., 1991. Self-tinning and stand density. *Forest Science* **37**(2): 517-523.

ZEIDE, B., 1993. Analysis of growth equations. *Forest Science* **39**(3): 594-616.

ZULLINGER, E.M., RICKLEFS, R.E., REDFORD, K.H., MACE, G.M., 1984. Fitting sigmoidal equations to mammalian growth rates. *J. Mamm.* **65**(4): 607-636. As mentioned in Karkach (2006).

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Appendix

Consider all SUPS of a given species, with identical age structure, exhibiting the classes the same number of years. The time-space symmetry between SEPS, and SUPS prescribes the following properties in SUPS:

a) The structure of the SUPS is affected by the index of performance of its symmetric SEPS.

b) In the age structure, only the number of trees per class per area unit (frequencies, y_{-21}) decreases with age.

c) All classes of the same SUPS occupy the same area.

d) The variables y_{0j} are identical in all classes, of the same SUPS.

e) In a SUPS, consider the average values of y_{1j} ,j=1,2,3, and two different age classes. The ratio of the values of two distinct classes is the same in all SUPS of the species.

f) Consider the values of the variables y_{1j} , j=4, and two different age classes. The ratio of the values of two distinct classes is the same in all SUPS of the species.

g) The allometric relationships, as the 3/2 power law, are verified in the space continuum

In BARRETO (1991), I published the size structure of a SEPS, of *Pinus pinaster.* To illustrate the capabilities of my theory, in table 1A, I display the age, and size structures of its symmetric SUPS. I consider a forest with 100 hectares.

If I use the structure of the SEPS exhibited in BARRETO (1991), and to each age I apply the Shannon-Wiener index (*Hs*), to the frequencies of the dbh classes, I always obtain Hs=1.03. If I apply the same procedure to the size structures of each age class, in table 1A, I also obtain Hs=1.03. If to the standing volume of the SEPS, and the SUPS, I apply the same procedure, I always find Hs=0.94. I used natural logarithms to calculate *Hs,* instead of logarithms to the base 2.

These constancies are caused by the neutrality of self-thinning, the self-similarity of SPS, and the time-space symmetry between SEPS, and SUPS.

Table 1A - *The age, and size structures of a SUPS of Pinus pinaster, in a good site. The stand area is equal to 100 hectares.* y_{11} *represents the mean dbh of the size class;* y_{-21} *is the number of trees per 100 ha;* $y_{14} = m^3/100$ *ha. According to the longevity of the species, there is no trees older than 100 years. Total number of trees is 47872, and total standin volume is 38930* $m^3/100$ *ha*

Class I:15-34 years			**Class II:35-54 years**			**Class III:55-74 years**			**Class IV:75-94 years**			**Class V:>95 years**		
y_{11}	y_{-21}	y_{14}	y_{11}	y_{-21}	y_{14}	y_{11}	y_{-21}	y_{14}	y_{11}	y_{-21}	y_{14}	y_{11}	y_{-21}	y_{14}
11	182	7	15	98	10	17	78	11	17	73	11	>17.8	17	3
16	3589	465	23	1926	634	25	1541	709	26	1430	736	>26.7	349	184
22	11196	3445	30	6007	4703	34	4806	5258	35	4461	5458	>35.6	1088	1364
28	4421	2661	38	2372	3632	42	1898	4061	44	1762	4215	>44.5	430	1054
33	60	53	45	32	72	51	26	80	52	24	83	>53.4	6	21
	19448	6631		10435	9051		8349	10119		7750	10503		1890	2626

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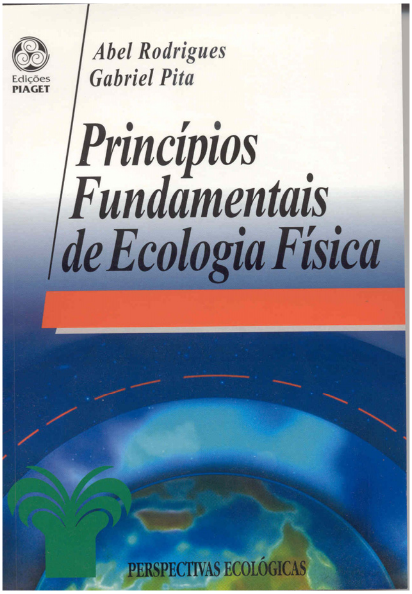
Recensões

Abel Rodrigues e Gabriel Pita 2014 – *Princípios Fundamentais de Ecologia Física.* Edições Piaget, Lisboa, 388 pp.



É um truísmo afirmar que todos estamos sujeitos ao ambiente em que vivemos e que dele obtemos a água e os alimentos que sustentam os processos biológicos, os recursos energéticos e os materiais. E todos nós, a uma escala global, estamos hoje muito mais alertados quanto ao impacte global do clima em todos os aspetos da nossa vida doméstica, da indústria e comércio, mesmo desconhecendo-se, na sua generalidade, a dimensão da ameaça ambiental global. Durante muitos anos a tónica dominante do enfoque da formação nas áreas ambientais, onde as condições do ambiente são decisivas para os resultados dos processos produtivos, dirigiu-se na sua generalidade para os estudos das relações com os seres vivos numa ótica dominada por conceitos empíricos e genéricos sem uma base quantificada e não abordando de forma compreensiva os fenómenos físicos subjacentes à mecânica dos fluídos onde se incorpora a transmissão de calor e massa que determinam as problemáticas da evapotranspiração e dos fluxos verticais de gases como o dióxido de carbono em cobertos vegetais. Faltava assim, na generalidade da literatura, mormente na portuguesa, uma abordagem integrada do quadro analítico necessário à compreensão dos processos atmosféricos inerentes à camada superficial, correspondendo até alturas inferiores a 1 km.

As metodologias e os conceitos da termodinâmica dos meios contínuos, assim como a utilização de métodos analíticos mais elaborados na análise dos fluxos de energia e massa em campo aberto, são considerados essenciais aos estudos da ecofisiologia, principalmente se pretendermos compreender, de uma forma intelectiva consistente, o comportamento dos sistemas ecológicos e, em termos práticos, a importância das escolhas dos modelos e do delineamento espacial dos sistemas florestais. É por reconhecer-se a necessidade de uma base experimental devidamente quantificada que a disciplina da biofísica ecológica está em rápido crescimento.

Neste contexto, o livro agora publicado veio trazer para esta área científica um importante contributo, não só com a exposição dos conceitos teórico-práticos necessários para uma abordagem inteligível dos balanços de massa e energia, importantes para a compreensão dos fenómenos de evapotranspiração e dos fluxos verticais de gases em cobertos florestais, e do enquadramento matemático necessário à sua quantificação e da inferência desses fluxos na explicitação do comportamento da vegetação na formação de microclimas ou nos fluxos de matéria incorporados ou perdidos nos respetivos ecossistemas. Dir-se-á mesmo que a ecofisiologia clássica não tem sido capaz de transpor resultados obtidos com o micro tratamento individualizado da planta para uma perspetiva do meta-comportamento do povoamento.

O livro agora publicado pela editorial Piaget compreende 7 capítulos e 2 anexos onde se explanam os conceitos básicos da física e da matemática nos tópicos relevantes à compreensão das leis do movimento a vários níveis da atmosfera, à humidade atmosférica e aos princípios de transferência de calor e de massa assim como às particularidades dos dispositivos experimentais transpostos do laboratório para céu aberto e se apresenta a descrição das metodologias, equipamentos e medidas experimentais, bem como os erros e incertezas inerentes às medições efetuadas.

Assim, e de uma forma breve quanto ao conteúdo, naturalmente denso, deste livro que oferece uma visão compreensiva das matérias chave da biofísica ecológica explicitando os conceitos e o seu desenvolvimento analítico, temos que no capítulo (I) é feita uma caraterização geral da camada limite da atmosfera sendo que os capítulos (II e III) são dedicados à caraterização dos fluxos verticais de quantidade de movimento, de calor sensível e de gases como o dióxido de carbono e o vapor de água em cobertos vegetais.

De forma mais detalhada, o cap. II é dedicado ao método aerodinâmico, baseado nos princípios aerodinâmicos da camada de mistura e das relações dos gradientes de fluxo, sendo o cap. III dirigido ao desenvolvimento dos princípios da metodologia de covariância turbulenta como base para a abordagem dos fenómenos de turbulência na camada atmosférica junto ao solo.

Sendo os escoamentos atmosféricos de natureza predominantemente turbulentos, estando associados a efeitos convectivos que são os principais responsáveis pela grande difusidade da turbulência, e consequentemente, do incremento dos processos de transferência de calor, e de massa assim como das flutuações na concentração do CO_2, os autores apresentam um desenvolvimento aprofundado das hipóteses para a análise dos parâmetros micrometeorológicos e dos procedimentos experimentais necessários à compreensão da dissipação da energia cinética e para o seu significado na difusão, quer do dióxido de carbono, quer do vapor de água, e das suas alterações em função do período diurno ou noturno, bem como da variabilidade dimensional do balanço de energia cinética em determinado local. Sendo importante a análise espectral da energia turbulenta para a compreensão das transferências de energia cinética, os autores dedicaram ao tratamento espectral das flutuações deste tipo de escoamento um cuidado particular, não só do ponto de vista matemático, como também no desenvolvimento do dispositivo experimental, da coleta, tratamento e validação do manancial de dados colhidos no campo.

O cap. IV foi dedicado à especificação dos processos de transferência vertical de energia e massa nos cobertos florestais para a avaliação da grandeza daqueles parâmetros que se relacionam com a perda de água, a erosão do solo ou o microclima no interior do coberto desses povoamentos. Em termos experimentais os autores exploram uma aplicação generalizada do método de covariância turbulenta na análise dos contributos de alguns dos cobertos florestais portugueses para o sequestro do carbono, e que possibilitou o conhecimento alargado sobre os principais fatores explicativos da variabilidade anual e sazonal dos componentes do balanço de carbono assim como das interações entre os fluxos de carbono, o vapor de água e entre variáveis físicas e fisiológicas.

A importância do conhecimento dessas grandezas é determinante na escolha das formas de coberto adotadas, nomeadamente numa silvicultura predominantemente artificial onde o esquema de plantação, o tratamento e a composição determinam comportamentos diversos na penetração e na transmissão da radiação, assim como na velocidade do ar que regula o microambiente e o desenvolvimento das plantas através das trocas de dióxido de carbono, calor e vapor de água, para já não esquecer o sequestro de carbono pelos cobertos florestais.

O cap. V faz uma caracterização introdutória da camada limite superficial em cobertos urbanos e declives suaves com o objetivo de confronto com o que se passa com os cobertos vegetais, o que naturalmente poderá fornecer um suporte teórico para futuras abordagens aos problemas envolvidos com a ecologia da paisagem ou ainda na explicação dos padrões espaciais que ocorrem nos ecossistemas. O cap. VI está dirigido para o estabelecimento de balanços de energia em vários tipos de coberto para o que desenvolve os processos fundamentais das trocas de calor por condução, convecção e radiação.

Tendo os autores deste livro conferido uma louvável importância didática ao livro que agora publicam, reservaram o cap. VII para um conjunto alargado de exemplos de aplicação, problemas e exercícios que serão uma ajuda importante para os que se iniciam no campo da ecologia física. Os anexos I e II estão dedicados às questões da instrumentação micrometeorológica e aos procedimentos de medição assim como aos tópicos básicos sobre as leis do movimento e da evaporação.

Uma valia importante deste livro, para além dos desenvolvimentos cuidados do tratamento teórico-matemático das principais variáveis que expressam os balanços de massa e energia, é a do trabalho pioneiro e de rigor científico impresso pelos autores ao tratamento experimental de que se destacam as medidas dos fluxos de dióxido de carbono e da avaliação dos fluxos de energia. Os resultados obtidos pelos autores, o cuidado e rigor postos nos dispositivos de medida e no tratamento de dados, nos erros e incertezas inerentes aos parâmetros avaliados são dos raros obtidos em Portugal na área dos fluxos de energia e nas áreas de caracterização dos fluxos de quantidade de movimento, calor sensível e gases, principalmente de CO_2. Este rigor científico e o sólido desenvolvimento teórico-matemático, aliado à vantagem de ter sido escrito em Português, conferem a este livro elevada importância para aqueles que queiram abalançar-se a estudos aprofundados na área da biofísica ambiental, da ecofisiologia e da ecologia.

Importa que este livro de base na área ambiental seja devidamente aproveitado para que o importante conhecimento desenvolvido seja traduzido em medidas concretas a incorporar nas intervenções florestais que minimizem os parâmetros suscetíveis de reduzirem o fluxo de energia e massas de que depende a produtividade dos povoamentos ou que maximizem os parâmetros que influenciam positivamente o aumento da fotossíntese e, portanto, da biomassa e do sequestro de carbono. É evidente que o alcance deste desiderato concernente à incorporação de conhecimento na cadeia de valor da produção, desafia a instituição responsável por essa missão, cujo ciclo é de médio longo-prazo, a desenvolver as estratégias que se iniciam pelo acesso formalizado a matas experimentais públicas onde seja possível garantir dispositivos experimentais de campo devidamente controlados e de investimento de médio longo prazo necessário a este tipo de estudos sem o qual a fundamentação de medidas prescritivas quantificadas ao nível da produção serão sempre precárias.

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B) CABRAL, M.T., LOPES, F., SARDINHA, R.A., 1993. Determinação das causas da morte do sobreiro nos concelhos de Santiago de Cacém, Grândola e Sines. Relatório Síntese. *Silva Lusitana* **1**(1): 7-24.

C) SILVA, R., PÁSCOA, F., MARQUES, C.P., 1991. Modelação dinâmica dos povoamentos de pinheiro bravo. In *Comunicações do I Encontro Sobre Pinhal Bravo, Material Lenhoso e Resina*, SPCF/ESAC/CFC, Coimbra, pp. 123-130.

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