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Efectos a longo prazo do lume e tres axentes extintores no sistema solo-planta
Long- term effects of fire and three fire-fighting chemicals on a soil-plant system

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RESUMO / ABSTRACT

Este estudo avalía os impactos dos incendios forestais e os axentes químicos empregados na extinción, dende xusto despois dunha queima prescrita ata cinco anos máis tarde, nas propiedades do solo e no sistema solo-planta. Os solos sen queimar (NQ) comparáronse con solos queimados tratados só con auga (Q) ou con auga a que se lle engadiu: axente escumante (Q+E), polímero Firesorb (Q+F) ou polifosfato de amonio (Q+P). Tanto os solos (0-2 cm de profundidade) como o material foliar (*Ulex micranthus*, *Pterospartum tridentatum*, *Erica umbellata* e *Pinus pinaster*) analizáronse para o C e N total, $\delta^{15}N$, nutrientes, pH, N inorgánico e altura e cobertura da vexetación. Só o polifosfato amónico tivo efectos claros: a) concentracións significativamente superiores de N inorgánico e P no solo; b) maior crecemento, $\delta^{15}N$, N e P nas plantas. O axente escumante non afectou á cuberta vegetal; o Firesorb non tivo un efecto notable no mato, pero si a mortalidade máis alta de piñeiros.

The impacts of fire and fire-fighting chemicals (FFC) on soil properties and the soil-plant system were evaluated from just after the fire to five years later. Unburnt soils (US) were compared with burnt soils treated with water alone (BS) or with foaming agent (BS+Fo), Firesorb polymer (BS+Fi), or ammonium polyphosphate (BS+Ap). Soils (0-2 cm depth) and foliar material (*Ulex micranthus*, *Pterospartum tridentatum*, *Erica umbellata* and *Pinus pinaster*) were analysed for total-C, total-N, $\delta^{15}N$ and nutrients, as well as soil pH and inorganic-N and vegetation cover and height. Only the ammonium-polyphosphate chemical had clear effects: a) higher P and inorganic-N concentrations in soils; b) higher growth and $\delta^{15}N$, N, P in plants. The foaming agent did not affect vegetation cover, and Firesorb had no noticeable effect on shrubs but the highest pine mortality.

PALABRAS CLAVE / KEY WORDS

Incendio; solo queimado; axentes extintores do lume; $\delta^{15}N$; matogueira; árbores

Wildfire; burnt soil; fire fighting chemicals; $\delta^{15}N$; shrubs; trees

INTRODUCCIÓN

1. Os incendios forestais en Galicia

Igual que ocurre no resto de Europa, o monte en Galicia é o produto dunha actividade humana que "domestica o proceso de sucesión natural da vexetación preexistente". O bosque mixto caducifolio, xa degradado e en retroceso polo emprego recurrente do lume dende hai polo menos 6-8000 anos (KAAL et al., 2008, 2011), modificado na época romana coa introdución cultural do castiñeiro, reduciuse por talas masivas na Idade Media e modificouse definitivamente dende finais do século XIX (máis intensamente dende mediados do s. XX) cós monocultivos de *Pinus pinaster* (383.632 ha), *Pinus radiata* (59.198 ha) e *Eucaliptus globulus* (174.210 ha) que hoxe superan a superficie ocupada por formacións de frondosas autóctonas (375.922 ha).

O lume en Galicia, do mesmo xeito que en moitos outros lugares de Europa e do mundo (KUHLKEN, 1999; PYNE, 1997), ligado dende tempos prehistóricos ao uso agrosilvopastoral, pasou de ser unha técnica de construción e manipulación do agroecosistema a unha forma destrutiva de protesta. Os procesos acontecidos no tempo, como a regresión demográfica, o envellecemento da poboación rural e a adaptación dunha agricultura de policultivo de subsistencia a unha economía mercantil como a europea, desembocou nun desequilibrio territorial preocupante. As continuas presións socioeconómicas, políticas e culturais durante á segunda metade do século XX mermaron as posibilidades de futuro para o rural galego do mesmo xeito que sucedeu noutras zonas de Europa. A emigración masiva, o intervencionismo Estatal na ordenación dos usos do solo e a adhesión de España á Unión Europea en 1986, conforman os eixes de cambio no medio rural galego no que os incendios forestais se xeneralizan como reflexo do conflictivo cambio da organización dos usos do territorio. As novas masas de arboredo de especies alóctonas de rápido crecemento, con menor resistencia natural ao lume (microclimas máis secos, follasca difícilmente descompoñible, densidades máis altas...) e boa rexeración tras o mesmo, carecen, salvo excepcións, dunha tradición silvícola que as respalde e os incendios forestais poñen de

INTRODUCTION

1. Wilfires in Galicia

As also occurs in other european countries, galician forests are the product of human activity, a "natural succession process domestication of the existing vegetation". Mixed deciduous forest, already degraded by cause of recurrent fires for at least 6-8000 years (KAAL et al., 2008, 2011), modified in Roman age with the introduction of the chestnut culture, was reduced by massive logging in the Middle Ages and definitely modified since the late nineteenth century (more intensely since mid-s. XX) with plantations of *Pinus pinaster* (383,632 ha), *Pinus radiata* (59,198 ha) and *Eucalyptus globulus* (174,210 ha), now surpassing the area occupied by native broadleaved formations (375,922 ha).

The fire in Galicia, as in many other parts of Europe and the world (KUHLKEN, 1999; PYNE, 1997), linked from prehistoric times to agrosilvopastoral use, has changed from being an agroforestry construction and manipulation technique to being a destructive form of protest. The processes over time, as demographic decline, rural population ageing and the adaptation from subsistence polyculture farming to a market economy ended in a territorial imbalance. Continued economic, political and cultural pressures, during the second half of the twentieth century, dwindled future possibilities for rural Galicia as has happened in other parts of Europe.

Mass emigration, state intervention in the management of land use and Spain joined the European Union in 1986, conform the axis of change in Galicia. Forest fires become widespread reflecting the conflictive change of land use organization. The new plantations of fast-growing exotic species, with less natural fire resistance (drier microclimates, hardly decomposable litter, higher densities,...) and good feedback after it, are lacking of a forestry tradition and wildfires highlight the poor conditions of their growth.

manifesto a precariedade das condicións de crecemento das mesmas.

En Galicia, entre 1991 e 2010, producíronse 175.000 incendios forestais que queimaron unhas 510.000 ha, con graves danos ecolóxicos e económicos (http://www.marm.é/é/biodiversidade/temas/defensa-contra-incendios-forestais/estadisticas-de-incendios-forestais.html). A catástrofe de 1989 con máis de 8.000 incendios e 200.000 ha queimadas, propiciou a creación por parte da Xunta de Galicia dun custoso sistema de loita contra incendios que investía esforzos e recursos fundamentalmente en extinción. O destrutivo episodio de incendios que sufriu España en 2006, con máis de 150.000 ha queimadas (96.000 ha en Galicia) propiciou a aplicación de novas medidas de loita contra incendios máis centrada no manexo forestal e os aspectos preventivos. Con todo, ante as dificultades dunha aplicación eficaz e o tempo requirido para un cambio en canto a prevención de incendios (un 90% dos cales son provocados), e como parece evidente que Galicia se enfrontará á mesma catástrofe no futuro, unha parte importante do orzamento séguese destinando á extinción dos incendios. Neste escenario, que se manterá previsiblemente ata o medio prazo, o estudo das repercusións que as tarefas de extinción teñen nos ecosistemas é do máximo interese.

2. Efectos dos incendios sobre os ecosistemas forestais

Os efectos do lume nos ecosistemas son o resultado da liberación durante a combustión de grandes cantidades de enerxía térmica, un 10-15 % da cal é absorbida ou transmitida directamente ao solo. Ningún lume é igual a outro, de modo que é unha cuestión clave coñecer as súas características: liberación de enerxía térmica, estación do ano, extensión e tipo de lume, frecuencia, carga e tipo de combustibles dispoñibles, clima e topografía.

O solo é unha parte do ecosistema moi importante que se ve afectada, tanto na súa capa orgánica como mineral.

2.1. Efectos do lume sobre as características fisico-químicas do solo

Varias propiedades do solo claves na sostenibilidade, como estrutura, porosidade, infiltración, réxime térmico

In Galicia, between 1991 and 2010, there were 175,000 wildfires that burned about 510,000 ha, with serious ecological and economic damage (http://www.marm.es/es/biodiversidad/temas/ defense-against-fire-forest / statistics-of-fire-forestales.html). The catastrophe of 1989 with more than 8,000 fires and 200,000 ha burnt, led to the creation by the galician regional government a costly firefighting system in which efforts and resources were invested primarily in extinction but obviated forest management and implementation preventive policies development.

The destructive fire episode suffered by Spain in 2006, with more than 150,000 ha burned (96,000 ha in Galicia) led to the implementation of new measures to combat fires more focused on forest management and preventive aspects. However, given the difficulties of successful implementation and the time required for a change in terms of fire prevention (90% of wilfires are human caused), it seems clear that Galicia will face the same disaster in the future. An important part of the budget still goes to the extinction of fires so, in this scenario, expected to be maintained even in the medium term, the study of the firefighting impact on ecosystems is of great interest.

2. Effects of fire on forest ecosystems

Fire effects on ecosystems result from the release during combustion of large amounts of thermal energy, 10-15% of which is absorbed or transmitted directly to the ground. No fire is like another, so is a key issue to know their characteristics: thermal energy release, season, extent and type of fire, fire frequency, load and type of available fuels, weather and topography.

Soil is a very important part of the ecosystem that is affected, both in organic and mineral layer.

2.1. Effects of fire on the physico-chemical characteristics of the soil

Key soil properties on sustainability, as structure, porosity, infiltration, temperature and water storage, can be deeply affected by the fires (POWERS et al., 1990).

e almacenamiento de auga, poden verse profundamente afectadas polos incendios.

O pH do solo aumenta co quentamento debido á desnaturalización dos ácidos orgánicos, a alcalinidade das cinzas (pH = 9-13,5) e o descenso da capacidade de cambio do solo ao eliminarse unha fracción moi densamente cargada e con alta capacidade para reter catións.

O lume pode afectar á estrutura do solo ao alterarse os minerais da fracción arxila, se se exceden os 500 ºC (TAN et al., 1986), e pola combustión da materia orgánica. Cando a estrutura do solo se degrada, os macroporos (> 0,6 mm de diámetro), responsables da infiltración da auga no solo, vólvense limitantes, de forma que a escorrentía superficial aumenta. Tanto a vexetación como a follasca mitigan o impacto da choiva no solo; se son consumidas polo lume, a superficie do solo espido pode selarse ante o impacto das pingas de choiva aumentando a escorrentía superficial. As consecuencias son unha diminución da humidade do solo, a erosión dos horizontes orgánicos e o lavado de cinzas ricas en nutrientes.

Outra consecuencia nos solos queimados é a repelencia a auga debida á formación dunha discreta capa, paralela á superficie do solo, de compostos orgánicos hidrofóbicos que recubren os agregados e os minerais (MATAIX-SOLERA & DOERR, 2004) e impide que a auga os humedeza, reducindo moito a infiltración; en ladeiras queimadas con pendente a hidrofobicidade pode acelerar a erosión e, xa que logo, a degradación do ecosistema.

2.2. Efectos do lume sobre a materia orgánica e os nutrientes do solo

Os solos queimados perden inexorablemente materia orgánica (MOS), en maior ou menor grado dependendo da severidade do lume (SIMARD et al., 2001). O horizonte orgánico é un compoñente crítico da sostenibilidade dos ecosistemas pois reduce a erosión, axuda na termoregulación, serve de hábitat e sustrato para a biota do solo e pode ser a principal fonte de nutrientes fácilmente mineralizables.

Entre os principais efectos do lume sobre a MOS, GONZÁLEZ-PÉREZ et al. (2004) enumeran: a) eliminación de grupos externos de osíxeno, que conduce a materiais menos solubles, b) redución da cadea alquílica de

Soil pH increases with warming due to denaturation of the organic acids, the ashes alkalinity (pH = 9 to 13.5) and the decline in soil exchange capacity due to the elimination of a densely loaded fraction and with high capacity to retain cations.

Fire can affect the soil structure by altering the clay mineral fraction, if it exceeds 500 °C (TAN et al., 1986), and by organic matter combustion. When soil structure degrades, the macropores (> 0.6 mm in diameter), responsible for the infiltration of water into the soil, become limiting, so runoff increases. Both vegetation and litter mitigate the impact of rain on the ground, if consumed by the fire, the bare soil surface can be sealed by the impact of raindrops, greatly increasing surface runoff. The consequence is a reduction of soil moisture, erosion and washing of organic nutrient-rich ash.

Another consequence is soil water repellency due to the formation of a discrete layer, parallel to the soil surface, of hydrophobic organic compounds overlying soil aggregates and minerals (MATAIX-SOLERA AND DOERR, 2004) which reduces wet and infiltration; on burned hillside hydrophobicity can accelerate erosion and hence the degradation of the ecosystem.

2.2. Effects of fire on soil organic matter and soil nutrients

Burnt soils lose inexorably organic matter (SOM) to a greater or lesser degree depending on the severity of the fire (SIMARD et al., 2001). The organic horizon is a critical component of the sustainability of ecosystems by reducing erosion, providing habitat for soil biota, aids in thermoregulation and may be the main source of readily mineralized nutrients.

The main effects of fire on the MOS, GONZÁLEZ-PÉREZ et al. (2004) are: a) elimination of external oxygen groups, which leads to less soluble materials, b) reduction of the alkyl chain alkanes, fatty acids and alcohols, c) aromatization of lipids and sugars, d) formation of heterocyclic N compounds, e) condensation of macromolecular humic substances, f) production of an almost unalterable component, called *black carbon*, which is originated at temperatures between 250 and 500 °C due to alcanos, acedos grasos e alcohois, c) aromatización de lípidos e azucres, d) formación de compostos heterocíclicos de N, e) condensación macromolecular de sustancias húmicas, e f) produción dun compoñente case inalterable, o chamado *carbono negro* que se orixina a temperaturas entre 250 e 500 ºC debido á combustión incompleta (carbonización) de residuos de madeira (BALDOCK & SMERNIK, 2002).

Os efectos do lume sobre a dispoñibilidade biolóxica do N do solo presentan un paradoxo moi debatido durante anos (MCKEE, 1982). Unha parte deste elemento, limitante para todos os organismos vivos, pérdese fácil e directamente por combustión ou por volatilización de $N\text{-}NH_3^-$, (FISHER & BINKLEY, 2000); pero, outra parte das formas orgánicas de N convértense en formas inorgánicas ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$) fácilmente asimilables polas plantas, aínda que, dependendo da intensidade das precipitacións post-incendio, parte do $N\text{-}NO_3^-$ pode perderse rápidamente por desnitrificación, lixiviación ou escorrentía. A importancia dunha rápida recolonización polas plantas para a conservación do N no solo de zonas queimadas demóstrase claramente nos estudos de WESTON & ATTIWILL (1990).

Nos bosques o solo almacena case todo o P (94-98 %), pero a pequena fracción contida na vexetación e follasca é moi importante pois o ciclo do P desenvólvese principalmente a través das reservas de P orgánico nestes compartimentos, cuxa eliminación simultánea polo lume esgota as reservas de P na biomasa e necromasa a un ritmo superior ao aporte de P pola meteorización de minerais (DEBANO et al., 1998).

Posto que son necesarias temperaturas moi altas (760 a 1240 ºC) para vaporizar K, S, Na, Mg e Ca (> 760 ºC), S (> 800 ºC), Na (> 880 ºC), Mg (> 1107 ºC) e Ca (> 1240 ºC) (WEAST, 1988), as perdas por volatilización son reducidas e as súas concentracións aumentan considerablemente na solución do solo logo dunha queima. KHANNA et al. (1994) diferenciaron tres clases de nutrientes nas cinzas en función da súa solubilidade: a) K, S e B, moi solubles, b) Ca, Mg, Si e Fe, relativamente insolubles e c) P, moi insoluble.

2.3. Efectos do lume sobre os microorganismos do solo

O lume reduce a biomasa da comunidade microbiana (PRIETO-FERNÁNDEZ et al., 1998) e altera a súa

incomplete combustion (carbonization) of wood (BALDOCK AND SMERNIK, 2002).

The effects of fire on the biological availability of soil N present a paradox debated for years (MCKEE, 1982). Part of this element, limiting for all living organisms, is easily lost by combustion or volatilization of $N\text{-}NH_3$ (FISHER AND BINKLEY, 2000); but, another part of the organic N forms are converted into inorganic forms ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$) easily assimilated by plants, although, depending on the intensity of post-fire rainfall, part of the $N\text{-}NO_3^-$ can be quickly lost by denitrification, leaching or runoff. The importance of rapid recolonization of burned areas by plants for soil N conservation is clearly demonstrated in the studies of WESTON AND ATTIWILL (1990).

In forests soil stores almost all P (94-98%), but the small fraction contained in vegetation and litter is very important as the P cycle develops primarily through organic P stocks in vegetation and litter. The fire causes depletion in the compartment biomass + necromass P faster than the supply of P by weathering of minerals (DEBANO et al., 1998).

Since they are required very high temperatures (760 to 1240 °C) to vaporize K, S, Na, Mg and Ca (> 760 °C), S (> 800 °C), Na (> 880 °C), Mg (> 1107 °C) and Ca (> 1240 °C) (WEAST, 1988), volatilization losses are reduced and their concentrations increase significantly in the soil solution after a burn. KHANNA et al. (1994) differentiated three classes of nutrients in the ashes on the basis of their solubility: a) K, S and B, very soluble, b) Ca, Mg, Si and Fe, relatively insoluble c) P, very insoluble.

2.3. Effects of fire on soil microorganisms

Fire reduces the microbial community biomass (PRIETO-FERNÁNDEZ et al., 1998) and alters its specific composition, because it affects fungal community more than bacterial (BAATH et al., 1995). In extreme cases, the upper soil layer can be completely sterilized. Adverse effects on soil biota may be due to some organic pollutants (dioxins, furans and polycyclic aromatic hydrocarbons) produced in combustion processes.

composición específica, pois a comunidade fúnxica redúcese máis que a bacteriana (BAATH et al., 1995). En casos extremos, a capa superior do solo pode esterilizarse completamente. Os efectos adversos sobre a biota do solo poden deberse tamén a algúns contaminantes orgánicos (dioxinas, furanos e hidrocarburos aromáticos) producidos polos procesos de combustión.

2.4. Efectos do lume sobre a vexetación

O compoñente do ecosistema no que os efectos dos incendios se fan máis visibles é a cuberta vexetal, que constitúe o principal combustible.

2.4.1. Rexeración do estrato herbáceo e arbustivo

As herbáceas, procedentes do banco de sementes do solo ou da colonización dende zonas próximas, xerminan con rapidez aproveitando o aumento da dispoñibilidade de nutrientes e a falta de competidores leñosos pola luz.

A rexeración post-incendio en áreas de mato segue tres estratexias: rebrote de cepa das especies que resisten a destrución da parte aérea, xerminación de especies de carácter pirófito e invasión de especies oportunistas efémeras (CASAL et al., 1984). Estas estratexias determinan a composición de especies e a súa abundancia na comunidade vexetal.

Das 5 especies arbustivas galegas estudadas por REYES et al. (2009), *Pterospartum tridentatum*, *Ulex europaeus*, *Ulex minor*, *Ulex micranthus*, *Genista triacanthos* e *Erica umbellata,* só a última é incapaz de rebrotar. Aínda que con serias dificultades para competir co seu potente rebrote de cepa, todas as especies rebrotadoras poden tamén recolonizar a partir de semente, cuxa germinación é estimulada polo choque térmico (REYES & REGO, 2000; REYES & CASAL, 2008). A maior estimulación dáse en *U. europaeus* e a combinación co rebrote de cepa fai que esta especie sexa a que máis posibilidades ten de colonizar os espazos baleiros logo dun lume. En xeral, no mato atlántico afectado por lumes recurrentes cúmprese a hipótese de PAUSAS (1999) segundo a cal o rebrote acada máis relevancia que a xerminación; así, obsérvase que as especies non rebrotadoras e as especies rebrotadoras débiles son eliminadas da comunidade mentres que as rebrotadoras fortes aumentan as súas poboacións.

2.4. Fire effects on vegetation

The ecosystem component in which the effects of the fires become more visible is the cover, that is the main fuel supply.

2.4.1. Regeneration of herbaceous and scrub

Forbs, from the soil seed bank or surrounding areas colonization, germinate rapidly due to increased nutrient availability and the lack of wood competitors for light.

The post-fire regeneration in scrub areas follows three strategies: respruting of species that resist aerial parts destruction, pyrophytic species germination and invasion of opportunistic ephemeral species (CASAL et al., 1984). These strategies determine the species composition and abundance in the plant community.

Of the five galician shrub species studied by REYES et al. (2009), *Pterospartum tridentatum*, *Ulex europaeus*, *Ulex minor*, *Ulex micranthus*, *Erica umbellata* and *Genista triacanthos,* only the latter is unable to resprout. Although they have serious self-competive difficulties, all resprouting species may also colonize from seeds whose germination is stimulated by heat shock (REYES AND REGO, 2000; REYES AND CASAL, 2008). The greatest stimulation occurs in *U. europaeus* and combination with respruting facilitates the colonization of the empty spaces after a fire. Overall in the Atlantic scrubland affected by recurrent fires respruting reaches more relevance than germination (PAUSAS, 1999), so species that follow this strategy increase their populations, while weak and no resprouting species are eliminated from the community.

2.4.2. Tree regeneration

Pinus pinaster is the most widespread tree species in Galicia with 380,000 ha in monoculture plantations and 235,000 ha in mixed stands with hardwoods (XUNTA DE GALICIA, 2001) and also the most affected by fires. Although relatively resistant to injury by fire in stem, leaf scorch is a common cause of mortality and root damage favors pathogen attack.

2.4.2. Rexeración do estrato arbóreo.

O piñeiro do país (*Pinus pinaster*) é a especie arbórea máis estendida en Galicia cunhas 380.000 ha en plantacións monoespecíficas e 235.000 ha en masas mixtas con frondosas (Xunta de Galicia, 2001) e a máis afectada polos incendios. Aínda que é relativamente resistente a feridas por lumes no tronco, o chamuscado das follas é causa común de mortalidade e os danos nas raíces favorecen o ataque de patóxenos.

No caso de *Eucalyptus globulus*, segunda especie máis afectada polos incendios en Galicia, a estratexia de supervivencia é diferente: a) estratexia de rebrote (lignotubérculos no colo da raíz e xemas epicórmicas ao longo do tronco) moi favorable, e b) apertura de cápsulas debido á calor e abundantísima diseminación de sementes, ademais, a dunha grande capacidade colonizadora vía aire debida ao escaso peso da semente.

As carballeiras de *Quercus robur* e *Quercus pyrenaica* atópanse naturalmente en áreas máis húmidas e de mellor solo de forma que, aínda que tamén sofren o impacto dos incendios, non adoitan queimarse intensamente. Poden rebrotar de cepa, pero frecuentemente quedan feridos polo lume e son atacados por fungos que debilitan ao individuo.

3. Efectos da extinción de incendios sobre os ecosistemas

3.1. Impactos ecolóxicos da extinción de incendios forestais

Os impactos das actividades de extinción sobre os ecosistemas forestais poden ser importantes e incluso superar os efectos do incendio. Un recente cambio de paradigma de control de incendios traduciuse nunha maior atención por reducir ao mínimo os efectos negativos da extinción que poderían resumirse en:

- Erosión agravada pola construción de liñas de lume e vías de acceso.
- Compactación do solo por tránsito de vehículos pesados.
- Extracción de auga en cursos e masas de auga con avionetas e helicópteros que aumenta os sedimentos en suspensión, contribuíndo á turbidez da auga o que afecta á fauna acuática e ao seu hábitat.

In the case of *Eucalyptus globulus*, second species most affected by fires in Galicia, the survival strategy is different: a) a very favorable regrowth after fire (lignotubers in the root collar and epicormic buds along the trunk), and b) capsules open after being scorched in a fire, abundant seed dispersal and very good colonizing capacity because of the low seed weight.

The oak woods with *Quercus robur* and *Quercus pyrenaica* occur naturally in wetter areas and better soil so, although impacted by fires, not usually burn intensely.

3. Effects of firefighting in the ecosystem

3.1. Ecological impacts of forest fire

The impacts of wildfire fighting on forest ecosystems can be important and even may overcome the effects of the fire. Recentlty, increased attention is being paid to minimize negative effects of extinction that could be summarized as:

- Aggravated erosion by fire lines and roads construction.
- Soil compaction by heavy vehicles.
- The extraction of water with planes and helicopters causes sediment suspension in water bodies, contributing to water turbidity which affects aquatic life and its habitat.
- Removal of vegetation before the arrival of brigades. Deforestation, that also adversely affects the control of erosion, eliminates wildlife refuges (MCIVER AND STARR, 2000), can damage the regrowth of certain species (MCIVER AND STARR, 2000) and reduces insects populations that serve as food for many wildlife species (BLAKE, 1982).
- Artificial materials (metal posts, synthetic fabrics,...) and other consumables used by firefighting equipment (plastic pots, gloves, uniforms,...) can persist in the environment longer than the effects of fire if no suitable waste disposal.

- Eliminación da vexetación antes da chegada das brigadas contra incendios. A tála de árbores, ademais de repercutir negativamente no control da erosión, elimina posibles refuxios de vida silvestre (MCIVER & STARR, 2000), pode danar o rebrote de certas especies (MCIVER & STARR, 2000) e reduce as poboacións de insectos que serven de alimento a diversas especies de fauna silvestre (BLAKE, 1982).
- Os materiais artificiais (postes metálicos, tecidos sintéticos,...) e o resto de consumibles utilizados polos equipos de extinción (botes plástico, luvas, uniformes,...) poden perdurar no ambiente máis tempo que os efectos do lume se non hai unha eliminación de residuos adecuada.
- Posibles derrames de hidrocarburos e contaminación química polos produtos retardantes do lume que se lle engaden a auga.

3.2. Impactos ecolóxicos dos retardantes do lume empregados na extinción

Actualmente existe no mercado unha ampla variedade de produtos químicos utilizados na extinción de incendios forestais, pero os máis utilizados para controlar o lume clasifícanse en dúas categorías:

- Retardantes a longo prazo: produtos químicos baseados xeneralmente en N e P, que inhiben a combustión incluso tras a evaporación da matriz acuosa ata que son eliminados pola choiva ou o vento.
- Retardantes a curto prazo: inclúen ás escumas anti-incendios e aos axentes humectantes; son formulacións comerciais complexas cuxos compoñentes principais son disolventes, tensioactivos fluorocarbonados e tensioactivos hidrocarbonados. Estas substancias perden a súa eficacia coa evaporación de auga e a súa acción baséase en aumentar o efecto da auga inhibindo a súa evaporación, ademais de disolver a capa de ceras da vexetación (SCHLOBOHM & ROCHNA, 1988). A súa principal vantaxe reside na redución da cantidade de auga necesaria para controlar o lume.

- Potential oil spills.
- Chemical pollution by fire retardant products added to water.

3.2. Ecological impacts of fire retardants used in the extinction

Currently on the market there is a wide variety of chemicals used in extinguishing wildfires, but the most commonly used are classified into two categories:

- Long-term retardants: chemicals generally based on N and P, which inhibit combustion even after the evaporation of the aqueous matrix until they are eliminated by rain or wind.
- Short-term retardants: including foams and wetting agents. Those chemicals are complex commercial formulations whose main components are solvents, fluorocarbon surfactants and hydrocarbon surfactants. Short-term retardants lose their effectiveness with water evaporation and its action is based on increasing water effect by inhibiting its evaporation; also, they dissolve wax layer of the vegetation (SCHLOBOHM AND ROCHNA, 1988). Its main advantage lies in reducing the amount of water needed to control the fire.

Long-term fire fighting chemicals are increasingly use because they are very effective in controlling declared wildfires, especially in climatic areas prone to forest fires, like the Mediterranean basin (MORENO et al., 1998). Spain (300 Mg yr^{-1}) is one of the main consumers of these products in Western Europe and the Mediterranean; the most used is the Cross FR ammonium polyphosphate.

Os retardantes de chama a longo prazo teñen un uso cada vez máis xeneralizado debido a que funcionan como eficaces instrumentos no control de incendios xa declarados, especialmente en áreas climáticas propensas aos incendios forestais, por exemplo a conca mediterránea (MORENO et al., 1998). España (300 Mg ano^{-1}), é un dos principais consumidores destes produtos en Europa occidental e o Mediterráneo; o máis empregado é o polifosfato amónico FR Cross.

3.2.1. Toxicidade dos retardantes a longo prazo

Malia os beneficios que os retardantes a longo prazo proporcionan na extinción de incendios, a preocupación relativamente recente sobre o efecto destas sustancias nos ecosistemas materializouse en diversos estudos que indican, en varios casos, un potencial impacto medioambiental negativo, especialmente nos ambientes acuáticos. Os seus compoñentes activos, básicamente fertilizantes agrícolas como sulfatos e fosfatos de amonio, poden causar cambios no medio ambiente local e/ou efectos ambientais adversos se o tipo ou intensidade de uso é o suficientemente grande como para que estas sustancias, vertidas masivamente ao solo, pasen á vexetación e as augas subterráneas (BRADSTOCK et al., 1987; GIMÉNEZ et al., 2004; PAPPA et al., 2006). No pasado, supoñíase que os efectos do N e o P dos retardantes eran mínimos porque os aportes destes elementos eran puntuais e pouco frecuentes (HANDLEMAN, 1971). Con todo, dado que o N e o P son elementos limitantes para a productividade das augas superficiais, os retardantes do lume formulados con fertilizantes deben utilizarse con precaución preto dos recursos hídricos. O impacto sobre a calidade e o potencial de eutrofización das augas superficiais dependerá de varios factores, incluíndo a cantidade de nutrientes engadida, a productividade previa das augas afectadas, a estacionalidade e frecuencia dos aportes (FREEDMAN, 1995), así como numerosos factores específicos do lugar (clima, tipo de solo e contido en materia orgánica, cobertura vexetal,...).

En canto aos efectos sobre a vexetación, observáronse aumentos na produción de biomasa en pradeiras anuais de 6 Mg ha^{-1} a 12 Mg ha^{-1} logo da aplicación de retardantes con alto contido en fosfato amónico; mentres, o establecemento de especies nativas de

3.2.1. Long-term retardants toxicity

Despite the benefits provided by long-term retardants in fire suppression, relatively recent concern about the effects of these substances on ecosystems has resulted in several studies that indicate the potential negative impact, especially in aquatic environments. Its active components, mainly agricultural fertilizers as ammonium sulfates and phosphates, can change the local environment and/or cause adverse environmental effects if the type or intensity of use is large enough so that these substances, discharged to the soil, pass to vegetation and groundwater (BRADSTOCK et al., 1987; GIMÉNEZ et al., 2004; PAPPA et al., 2006). In the past, it was assumed that the effects of N and P in the retardants were minimal because the contribution of these elements were punctual and rare (HANDLEMAN, 1971). Nevertheless, N and P are water productivity limiting factors, so fire retardants base formulated with fertilizers should be used with caution near water resources. The impact on quality and potential for eutrophication of surface waters will depend on several factors, including the amount of nutrients added, the previous productivity of the waters concerned, seasonality and frequency of additions (FREEDMAN, 1995) and numerous site-specific factors (climate, soil type and organic matter content, vegetation,...).

Regarding the effects on vegetation, increases were observed in biomass production in annual pasture (6 ha^{-1} Mg to 12 Mg ha^{-1}) after application of ammonium phosphate retardants; meanwhile, native leguminous species were inhibited after treatment with these compounds (LARSON AND DUNCAN, 1982). The experiences of BRADSTOCK et al. (1987) showed that mature individuals of Myrtaceae, Proteaceae and Poaceae families showed no coverage declines after treatment with ammonium sulfate retardant, however, Mimosaceae and Fabaceae families were affected.

leguminosas resultaba inhibido tras o tratamento con estes compostos (LARSON & DUNCAN, 1982). As experiencias de BRADSTOCK et al. (1987) mostraron que individuos maduros das familias Myrtaceae, Poaceae e Proteaceae non experimentaban descensos na cobertura despois do tratamento con retardantes de sulfato amónico, mentres, si se vían afectadas as familias Fabaceae e Mimosaceae.

Os efectos nocivos dos retardantes a longo prazo sobre os animais estudáronse en aves e mamíferos e parecen ser mínimos; con todo, os efectos adversos (debidos á toxicidade do N-NH_3) en organismos acuáticos son notables, como o proban numerosos ensaios de laboratorio en especies de algas e zooplancton (MCDONALD et al., 1996), anfípodos (MCDONALD et al., 1997) e larvas de peixes (BUHL & HAMILTON, 2000; GAIKOWSKY et al., 1996).

3.2.1. Toxicidade dos retardantes a curto prazo

A literatura científica sobre os impactos ambientais dos escumantes é moi limitada. No entanto, coa súa crecente popularidade como extintores de incendios (RAWET et al., 1996; ADAMS & SIMMONS, 1999), cada vez é maior a probabilidade de accidentes debido á súa aplicación en cursos de auga. A dilución destes compostos sucede con rapidez en cursos de auga rápidos, pero en corpos de auga menos dinámicos os efectos tóxicos poden persistir no tempo.

Os compoñentes tensioactivos contidos nos escumantes poden impactar na biota, xa que alteran a permeabilidade das membranas biolóxicas incrementando a absorción de contaminantes inorgánicos e orgánicos (ADAMS & SIMMONS, 1999). Ademais, tamén se consideran perxudiciais porque reducen a tensión superficial da auga, diminuíndo a capacidade dos organismos acuáticos para obter osíxeno (MCDONALD et al., 1996) ou alterando a súa movilidade (POULTON, 1996).

A maioría dos experimentos realizados son en laboratorio baixo condicións controladas e utilizando soamente o retardante "puro"; hai estudos que evaluaron os efectos de mesturas de retardantes aplicadas ás augas naturais, observándose diferentes efectos tóxicos, que

The harmful effects of long-term retardants on animals have been studied in birds and mammals, and appear to be minimal, however, adverse effects (due to N-NH_3 toxicity) in aquatic organisms are remarkable, as evidenced numerous laboratory tests in zooplankton and algae species (MCDONALD et al., 1996), amphipods (MCDONALD et al., 1997) and fish larvae (BUHL AND HAMILTON, 2000; GAIKOWSKY et al., 1996).

3.2.1. Short-term retardants toxicity

The scientific literature on the environmental impacts of the foaming agents is very limited. However, with its increasing popularity as fire extinguishers (RAWET et al., 1996, ADAMS AND SIMMONS, 1999), the likelihood of accidents is rising due to their application in water courses. The dilution of these compounds occurs quickly in rapid streams, but in less dynamic water bodies toxic effects may persist over time.

The components contained in foaming surfactants may impact the biota by altering the biological membranes permeability and so increasing the absorption of inorganic and organic contaminants (ADAMS AND SIMMONS, 1999). In addition, they reduce the surface tension of water, limiting the ability to obtain oxygen (MCDONALD et al., 1996) and altering mobility (POULTON, 1996) of aquatic organisms .

Most laboratory experiments are conducted under controlled conditions and using only the "pure" retardant. Some studies have evaluated the effects of retardant mixtures applied to natural waters and various toxic effects observed which may be modified by rain and runoff, topography, soil variables and uptake by vegetation. Essays, usually 48 or 96 hours, and acute toxicity tests indicate varying degrees of toxicity for algae (MCDONALD et al., 1996), plankton (MCDONALD et al., 1996), macroinvertebrates (MCDONALD et al., 1997) and fish (GAIKOWSKI et al. 1996; BUHL AND HAMILTON, 2000).

poden ser modificados pola choiva e escorrentía, a topografía, variables edáficas e captación por parte da vexetación. Ensaios, xeralmente de 48 ou 96 horas, e probas de toxicidade aguda indican distintos graos de toxicidade para algas (MCDONALD et al., 1996), plancton (MCDONALD et al., 1996), macroinvertebrados (MCDONALD et al., 1997) e peixes (GAIKOWSKI et al., 1996; BUHL & HAMILTON, 2000).

MATERIAL E MÉTODOS

1. Área de estudo

Este estudo foi realizado no Alto da Pedrada, con coordenadas UTM 29T ^{05}182 - ^{46}509 e altitude de 455 m s.n.m., localizado no Concello de Tomiño, provincia de Pontevedra.

Este área enmárcase no L.I.C. Baixo Miño, sito ao suroeste da provincia e cunha superficie de 2871 ha, e trátase dunha matogueira (de entre 50 e 60 cm de alto) situada a media ladeira formado por *Pterospartum tridentatum*, *Erica umbellata* e *Ulex europaeus*, con menor presencia de *Ulex micranthus*, *Ulex minor* e *Erica cinerea*. Segundo a clasificación bioclimática de RIVAS MARTÍNEZ (1979), esta formación vexetal corresponde á asociación *Erico umbellatae-Ulicetum micranthi*. Os solos desenvólvense sobre rocas graníticas (paragneises) con abundancia de Regosoles e Cambisoles (MACÍAS & CALVO DE ANTA, 2001); a parcela experimental é un Regosol léptico (IUSS WORKING GROUP WRB, 2006). Respecto da súa orientación e características bioclimatolóxicas podemos dicir que é un val aberto ao leste e protexido das influencias do oeste. A zona soporta unha importante carga de gando equino, ovino e caprino sobre a vexetación.

2. Deseño experimental

Seleccionouse un área de matogueira o suficientemente homoxénea e ampla para establecer as parcelas experimentais necesarias para os distintos tratamentos:

- Solo control non queimado (NQ)
- Solo queimado con 2 l m^{-2} de auga (Q)
- Solo queimado con 2 l m^{-2} de auga e RFC-88 ao 1% (Q+E)

MATERIAL AND METHODS

1. Study area

The experimental field, with UTM coordinates 29T ^{05}182 - ^{46}509, is located at Alto da Pedrada (Tomiño, Galicia, NW Spain) at an altitude of 455 m a.s.l.

This area is part of the L.I.C. Baixo Miño, located southwest of the Pontevedra province with an area of 2871 ha, and is a scrubland (50 to 60 cm high) formed by *Pterospartum tridentatum, Erica umbellata* and *Ulex europaeus*, and less presence of *Ulex micranthus, Erica cinerea* and *Ulex minor*. According to the bioclimatic classification of RIVAS MARTÍNEZ (1979), this corresponds to the *Erico umbellatae-Ulicetum micranthi* association. The soils are developed on granitic rocks (paragneises) with abundance of Regosols and Cambisols (MACÍAS AND CALVO DE ANTA, 2001); in the experimental plots the soil is a Leptic Regosol (IUSS WORKING GROUP WRB, 2006). The area is a valley opened to the east, protected from the influences of the west winds and supports a large load of horses, sheep and goats on vegetation.

2. Experimental design

After selecting an area of homogeneous slope, orientation, soil type and vegetation cover, within a total surface of 40 x 25 m, five in situ treatments were established:

- Unburnt soil (US) as a control
- Burnt soil with 2 l m^{-2} of water (BS)
- Burnt soil with 2 l m^{-2} of water plus foaming agent Auxquímica RFC-88 at 1% (BS+Fo)
- Burnt soil with 2 l m^{-2} of water plus Firesorb at 1.5%(BS+Fi)
- Burnt soil with 2 l m^{-2} of water plus FR Cross ammonium polyphosphate at 20% (BS+Ap)

The fire-fighting chemicals were selected amongst the most widely used in countries of the Mediterranean basin: RFC-88 is a foaming agent produced by Auxquimia SA (Mieres, Spain); Firesorb is a light cross-linked terpolymer of acrylic acid, acrylamide and acrylamidopropansulfonic acid sodium salt, manufactured by Evonik Stockhausen Gmbh (Krefeld, Germany); and FR Cross 134 P is an ammonium polyphosphate produced

- Solo queimado con 2 l m^{-2} de auga e Firesorb ao 1,5% (Q+F)
- Solo queimado con 2 l m^{-2} de auga e FR Cross 134 P ao 20% (Q+P)

O principal criterio de selección dos retardantes de chama foi o seu emprego xeralizado en extinción de incendios en España e países da cunca mediterránea: RFC-88 é un axente espumante producido por Auxquimia SA (Mieres, España), Firesorb é un terpolímero de ácido acrílico, acrilamida e sal sódico do ácido acrilamidopropanosulfonico manufacturado por Evonik Stockhausen Gmbh (Krefeld, Alemania), mentres que FR Cross 134 P é un polifosfato amónico producido por Chemische Fabrik Budenheim KG (Budenheim, Alemania; Zaragoza, España).

O deseño experimental materializouse no campo con 20 parcelas, 4 delas de mato non queimado e 16 que recibiron tratamentos con lume e que foron queimadas simultáneamente. A área experimental contou cun tamaño suficiente para, cunha queima a contravento (velocidade de propagación baixa), conseguir unha intensidade do lume e unha afección ao solo representativas de incendios non controlados. Extremáronse as precaucións para minimizar os danos ambientais, seleccionando un área de baixo interese ecolóxico, queimando só a superficie imprescindible e evitando a tempada de cría da fauna silvestre.

Os compostos retardantes de chama son aplicados con medios aéreos e, por tanto, é virtualmente imposible conseguir que caian só sobre a liña de lume. En consecuencia, hai tres escenarios posibles baixo condicións realistas de extinción de incendios: a) solos na liña de lume que reciben retardantes, tanto o solo como o retardante son afectados polo quentamento e a oxidación causadas polo lume, b) solos na área xa queimada pero próximos á liña de lume que, aínda quentes ou temperados, reciben o retardante, e c) solos na zona non queimada pero próximos á liña de lume que reciben o retardante e que non chegan a ser afectados polo lume. Habitualmente, os estudos céntranse nos dous últimos escenarios, probablemente debido ás dificultades para estudar a estreita e moi heteroxénea franxa do primeiro escenario.

by Chemische Fabrik Budenheim KG (Budenheim, Germany; Zaragoza, Spain).

In many cases, the fire-fighting chemicals are applied by aircraft and, therefore, it is virtually impossible that the chemical falls only in the fire line. Consequently, three scenarios are possible under realistic wildfire-fighting conditions: a) soils in the fire line that receive retardant, both the soil and the retardant being affected by the heating and oxidation caused by the fire; b) soils in the burnt area close to the fire line that, still hot or warm, receive the retardant; and c) soils in the unburnt area close to the fire line that receive the retardant but that are not affected by the fire. Usually studies focus on the last two scenarios, probably due to the difficulties in studying the narrow and very heterogeneous area of the first scenario.

After a prescribed fire (i.e. the fire is extinguished but the soil is still warm), burnt soil treatments were arranged in a fully randomized design with four replications and a 1 m separation around each plot (4 x 4 m), whereas the four unburnt soil replicates were established along the slope (18-19 %) and adjacent to the burnt ones.

In late winter, seven months after the prescribed fire, 4 one-year-old pine seedlings were planted in each plot to follow their development and to assess how the fire and flame retardants affect post-fire reforestation. During the first three years after plantation, height and basal diameter of pines were measured quarterly and then annually until the fifth year.

3. Methods

Five years after the prescribed fire, the soil-plant system was characterised. After removing the plant litter layer, soil samples were taken from the A horizon (0-2 cm depth) immediately before and after burning and 1, 3, 12 and 60 months after the prescribed fire. Five 15 x 15 cm squares, uniformly distributed around each plot, were sampled, mixed and thoroughly homogenized after sieving at 4 mm; soil sub-samples were air-dried, finely ground (< 100 µm) and stored for analysis.

Logo da queima controlada (co lume extinguido pero co solo aínda quente), os tratamentos do queimado foron distribuídos en base a un deseño aleatorio no que se establecían catro réplicas por tratamento e 1 m de separación entre cada parcela (4x4 m); mentres, as catro réplicas de solo non queimado dispuxéronse ao longo da pendente (18-19 %), adxacentes ás queimadas pero separadas 6 m das mesmas. A área de estudo illouse do gando mediante unha valado de malla cinexética e aramio de espiño para permitir o desenvolvemento da vexetación sen perturbacións.

A finais do primeiro inverno tras a queima (sete meses despois) en cada parcela implantaronse 4 piñeiros (*Pinus pinaster*) dunha savia co obxectivo de seguir o seu desenvolvemento a medio e longo prazo, de modo que o crecemento desta especie permitise evaluar os efectos provocados polo queimado e os distintos axentes retardantes de chama sobre o éxito da reforestación post-incendio. Durante os tres primeiros anos tras a súa implantación, a mediuse cada tres meses a altura e o diámetro na base dos piñeiros; posteriormente, as medidas fixéronse anualmente ata o quinto ano.

3. Métodos

As mostras de solo recolléronse do horizonte A (0-2 cm) inmediatamente antes e despois da queima prescrita, e 1, 3, 12 e 60 meses tras a queima. En cada data colléronse cinco cadrados de 15x15 cm, uniformemente distribuídos pola parcela, que foron mesturados, homoxeneizados e tamizados (< 4 mm). Posteriormente, a mostra de solo de cada parcela secouse ao aire e unha alícuota moeuse finamente (< 100 μm).

Antes da queima prescrita, tamén se fixo unha mostraxe da follasca en todas as parcelas; no laboratorio, este material secouse en estufa a 60 ºC e foi finamente moído (< 100 μm).

Tras cinco anos da queima prescrita, e con obxecto de evaluar a rexeración natural post-incendio, obtivéronse no campo os datos sobre características estructurais de cobertura e altura da vexetación de mato e a abundancia relativa das especies dominantes. En cada parcela fíxose un inventario florístico ao longo de tres transectos lonxitudinais paralelos á pendente tomando referencia cada

Before the prescribed fire, plant litter was also sampled in all plots, dried at 60ºC, finely ground (< 100 μm) and kept for analysis.

Three slope-down transects with sampling points every 25 cm were established within each plot (discarding 50 cm at each side to avoid possible edge effects); at every sampling point, the presence or absence of the four dominant shrub species was recorded, as well as their maximum height. Leaf material from the upper half of *Pinus pinaster*, *Ulex micranthus, Erica umbellata* and *Pterospartum tridentatum* was also collected; a fourth dominant shrub species, *Ulex europaeus*, was not collected because it was present only in two out five treatments. The plant material was washed successively with tap and deionized water, oven-dried at 60 °C for 48 h and finely ground in the same way as soils.

The dry matter content of soils, litter and plant material was assessed by oven-drying aliquots at 110 °C to constant weight. Soil pH was measured with a pH-meter (Metröhm, Switzerland) in 0.1 M KCl employing a soil: solution ratio of 1:2.5.

For the inorganic N analysis (NH_4^+-N and NO_3^--N) an extraction-diffusion method described previously (COUTO-VÁZQUEZ AND GONZÁLEZ-PRIETO, 2006) was used, but with 24 h diffusion periods at 50 °C. Soil available P weas extracted with acetic acid 0.5 M and analysed by simultaneous ICP-OES (Varian Vista Pro, Mulgrave, Australia).

The C and N contents of soils and litter, as well as their $\delta^{15}N$ values, were measured on finely ground samples (< 100 μm) with an elemental analyzer (EA) coupled on-line with an isotopic ratio mass spectrometer (Finnigan Mat, delta C, Bremen, Germany).

25 cm (excluíndo 50 cm en cada extremo para evitar posibles efectos de borde) das especies e a altura máxima na que tocaban unha vara perpendicular ao solo. En cada parcela, recolleuse material foliar de *P. pinaster*, *U. europaeus*, *P. tridentatum* e *E. umbellata*; no laboratorio, este material lavouse sucesivamente con auga corrente e desionizada, secouse en estufa a 60 ºC durante 48 h e moeuse ata un tamaño < 100 µm.

A materia seca do solo fresco, a follasca e o material vexetal verde determinouse mediante pesada de alícuotas e secado en estufa a 105 ºC durante 5 h. O pH do solo mediuse cun pH-metro (Metröhm, Switzerland) en KCl 0,1 M empregando unha relación solo: solución de 1:2,5.

Para a determinación do N inorgánico dos solos ($N\text{-}NH_4^+$ e $N\text{-}NO_3^-$) empregouse o método de extracción-difusión descrito por COUTO-VÁZQUEZ & GONZÁLEZ-PRIETO (2006). Os P asimilable dos solos extraeuse con ácido acético 0,5 M cunha relación solo: extractante 1:40 e cuantificouse mediante espectrometría de emisión óptica con fonte de plasma axustada inductivamente (Varian Vista Prol simultaneous ICP-OES, Mulgrave, Australia).

As determinacións de C e N total e de $\delta^{15}N$ en solos, follasca e material foliar (mostras moídas) realizáronse nun espectrómetro de masas isotópico (Finnigan Mat, delta C), cun analizador elemental axustado en liña.

4. Tratamento e análise estatística dos datos

Os datos das variables do solo para cada data analizáronse mediante unha ANOVA de dúas vías, introducindo como factores o tratamento e a data de mostraxe; os datos do material foliar recolleito aos cinco anos de queima analizáronse tamén cunha ANOVA de dúas vías, co tratamento e a especie como factores; en ambos casos empregouse o test de Levene para verificar a homoxeneidade de varianzas entre grupos. Nos casos en que houbo homocedasticidade (varianzas homoxéneas), as diferenzas significativas entre a media dos distintos grupos estabelecéuse usando o text de Bonferroni para comparacións múltiples ($p< 0,05$). Cando as varianzas foron desiguais, os datos orixinais sometéronse a transformacións Cox-Box para igualalos, e logo, as

4. Statisticals

Data of soil variables analysed at several dates after the fire were statistically analysed by two-way ANOVA, with treatment and sampling time as factors; data of foliar material 5 years after the prescribed fire were also analysed by two-way ANOVA, with treatment and species as factors. In both cases the Levene's test was used for verifying the equality of variances among groups. In the case of homocedasticity, significant differences among the mean groups were established at $P < 0.05$ using the Bonferroni test for multiple comparisons. In the case of unequal variances, the original data were subjected to Cox-Box transformations to obtain equality of variances, and significant differences among the mean groups were then established at $P < 0.05$ using the Bonferroni test for multiple comparisons.

All statistical analyses were done with SPSS 15.0. software.

diferenzas significativas entre grupos foron establecidas a p< 0,05 utilizando o text de Bonferroni para comparacións múltiples.

Todas as análises estatísticas foron realizados con SPSS 15.0.

RESULTADOS E DISCUSIÓN

1. Efectos do lume e os retardantes sobre o solo

O aumento significativo do pH_{KCl} observado tras a queima prescrita (0,4 unidades de pH en Q, 0,5 en Q+E y Q+F, e 0,9 en Q+P) debeuse, sen dúbida, á acumulación de cinzas ricas en óxidos e carbonatos de ións básicos e á redución de ácidos orgánicos (FISHER & BINKLEY, 2000). Os solos queimados aos que se lles engadiron retardantes sufriron un incremento adicional no pH que podería ser debido aos catións aportados polos devanditos químicos. Entre 3 meses e un ano despois o seu pH descendeu ata valores próximos aos do solo control, seguindo a tendencia normal en solos queimados que se debe ao lavado dos ións básicos durante a estación húmida (PRITCHETT & FISHER, 1987). O mesmo ocorreulles aos solos tratados con retardantes de chama, como tamén atoparon HOPMANS et al. (2007) nun traballo no que trataron solos non queimados co composto comercial Phos-Check, a base de sulfatos e fosfatos amónicos.

Aínda que o pH pode permanecer alto durante anos despois dunha queima (ANTOS et al., 2003), ao pouco tempo regresou aos niveis previos á perturbación. Con todo, como a acidificación do solo tivo lugar tanto nas parcelas queimadas como nas sen queimar, presumimos que outros factores deben estar desempeñando un papel importante na evolución post-incendio do pH e que un deles podería ser a exclusión do pastoreo na área de estudo, como tamén sinalan DORMAAR & WILLMS (1998).

Nin o lume nin os retardantes de chama teñen efectos a curto prazo sobre o N e/ou o C, probablemente polo aporte á superficie do solo de restos da vexetación parcialmente consumidos polo lume; tampouco HOPMANS et al. (2007) atoparon dierencia significativa algunha na MOS de solos non queimados tratados con Phos-Check. Por outra banda, a clara diminución na MOS observada un ano despois en todos os tratamentos con

RESULTS AND DISCUSION

1. Effects of fire and fire-fighting chemicals on soil chemical properties

The significant increase of soil pH_{KCl} observed after the prescribed fire was in all likelihood due to the accumulation of ashes rich in oxides and carbonates of basic ions and the reduction of organic acids (FISHER AND BINKLEY, 2000). The additional increment of soil pH_{KCl} in burnt soils treated with fire fighting chemicals (FFCs) could be due to the cations supplied by these chemicals. Between 3 months and one year after the fire the burnt soil pH decreases to values close to US, following a common trend in burnt soils, due to the leaching of basic ions during the wet season (PRITCHETT AND FISHER, 1987); the same was true for the burnt soils treated with FFCs, as was also found by HOPMANS AND BICKFORD (2003) in one of the two unburnt soils they treated with Phos-Check.

Although pH may remain elevated for years after the fire (ANTOS et al., 2003), it should slowly return to pre-disturbance levels and no significant long-term effect of fire or FFCs on soil pH_{KCl} was found. However, a significant long-term soil acidification (up to 0.25 pH units) was observed in all treatments and, consequently, other factors than post-fire pH evolution, probably grazing exclusion (see DORMAAR AND WILLMS, 1998), must play an important role in our case.

Neither the prescribed fire nor the addition of fire fighting chemicals influenced the soil C and N content in the short term; similarly, no significant differences were found by HOPMANS AND BICKFORD (2003) in SOM content of unburnt soils treated with Phos-Check. On the other hand, the SOM depletion observed one year later in all treatments with burnt soil may be the medium-term consequence of the fire-triggered erosion processes of burnt plots, which was reverted in the long term.

The $\delta^{15}N$ decrease in burnt soils just after the fire (0.2 to 0.5 ‰ (Fig. I)) was due to the N added to the soil surface by the ashes from living plants or litter (dominated by leguminous debris with $\delta^{15}N$= -1.1 ‰), which were impossible to differentiate from the upper soil layer ashes and, consequently, jointly sampled, leading to the decrease solos queimados pode ser unha consecuencia a medio prazo dos procesos erosivos promovidos ou desencadeados polo lume; este efecto revírtese a longo prazo.

O descenso inicial do δ ^{15}N (0,2 a 0,5 ‰ (Fig. I)) na capa máis superficial do solo xusto tras queima débese ao N aportado á superficie polas cinzas procedentes da follasca e a cuberta vexetal viva (dominada por leguminosas con un δ ^{15}N= -1,1 ‰), que foron imposibles de diferenciar das cinzas das partes máis superficiais do solo; así, a capa de 0-2 cm de solo tomada como mostra é unha mestura composta.

Observouse un incremento de δ ^{15}N en todas as parcelas queimadas (+2,22 a +2,57 ‰), evidente dende o terceiro mes (o primeiro en Q+P) e un ano despois con respecto a NQ; esto suxire que a queima desprazou, polo menos a medio prazo (1 ano), o balance de ganancias-perdas de N no solo cara a estas últimas, empobrecidas en ^{15}N (HÖGBERG et al., 1995). A longo prazo, t=5 anos, obsérvase un incremento significativo nos valores de δ ^{15}N nas parcelas de NQ e Q+F con respecto a t=1 e en todas as parcelas en comparación cos valores pre-queima. Este incremento do δ ^{15}N do solo, que afecta tanto ás parcelas queimadas como ás non queimadas, paralelo á progresiva acidificación do solo, podería estar relacionado coa exclusión do gando das parcelas experimentais.

Dende o primeiro momento despois da queima, e ata 5 anos despois, os solos queimados tratados con polifosfato amónico mostraron maior biodispoñibilidade de P e N (N-NH_4^+ e/ou N-NO_3^-) que nos outros tratamentos, básicamente debido á gran cantidade de P e N-NH_4^+ que contén este produto químico.

O aumento de N-NH_4^+ que ten lugar xusto despois do lume en todas as parcelas queimadas (Fig. II) é unha tendencia frecuente en solos recentemente queimados tanto no campo como en estufas de laboratorio (CHANDLER et al., 1983; PRIETO-FERNÁNDEZ et al., 1993). As máximas concentracións de N-NH_4^+ rexistráronse en Q+P onde, debido ao aporte polo polifosfato amónico, a concentración deste catión foi 200 veces superior ao promedio de NQ e 9-18 veces maior que a de Q, Q+E e Q+F. De igual xeito, en experimentos

in δ ^{15}N in the 0-2 cm soil layer. The increment in δ ^{15}N (+2.22 to +2.57 ‰) that was evident between three months (one month in BS+Ap) and one year after the prescribed fire in all burnt plots, compared with US, clearly suggests that the fire had a medium-term influence on N balance, promoting the outputs (nitrate lixiviation and/or ammonia volatilization), which are ^{15}N depleted (HÖGBERG et al., 1995). However, at t = 5 years δ ^{15}N increased significantly in US and BS+Fi plots with respect to t = 1 year and in all plots compared to respective pre-burn values. This δ ^{15}N increase, affecting both burned and unburned plots, parallel to the progressive soil acidification, could be related to cattle exclusion in experimental plots.

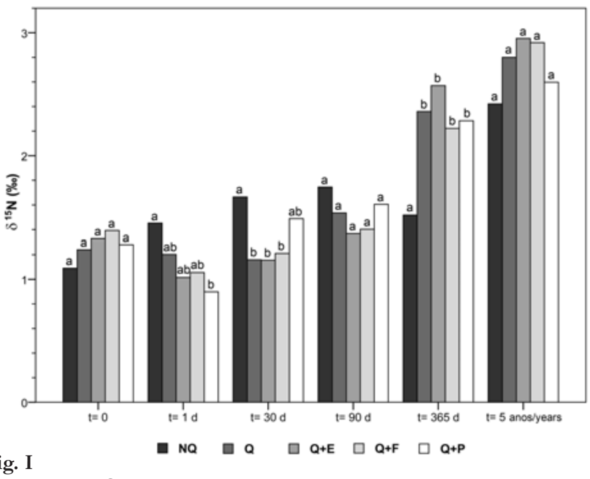

Fig. I
Evolución do δ ^{15}N do solo durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of δ ^{15}N in the 0-2 cm soil layer along five years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F,

The NH_4^+-N increase that takes place just after the fire in all burnt soil treatments (Fig. II) is a common tendency of recently heated or burnt soils (CHANDLER et al., 1983; PRIETO-FERNÁNDEZ et al., 1993), but the extremely high concentration of BS+Ap was very likely due to the NH_4^+-N supplied by the ammonium polyphosphate. Similarly, in field experiments with unburnt soils, HOPMANS AND BICKFORD (2003) also observed that Phos-Check (which contains ammonium polyphosphates and sulphates) stimulates a three to ten-fold increment in available N over initial values in the 0-20 cm soil layer, that disappeared within 2 months. The very high NH_4^+-N levels in BS+Ap, and its relative persistence de campo con solos non queimados, HOPMANS et al. (2007) observaron que o emprego de Phos-Check (que contén polifosfato-amónico e sulfatos) daba lugar a un aumento no N dispoñible de tres a dez veces por enriba dos valores iniciais na capa de solo de 0-20 cm, que desaparece ao cabo de 2 meses. Os niveis moi elevados de N-NH_4^+ en Q+P, e a súa relativa persistencia no tempo (> 3 meses), poderían condicionar a recuperación post-incendio da cuberta vexetal pois a toxicidade por N-NH_4^+ pode inhibir a xerminación das sementes (BRITTO & KRONZUCKER, 2002) e o establecemento dos plantóns. Este feito verificouse nunha experiencia de invernadeiro (os datos non se mostran) no que unha aplicación de polifosfato amónico, á dose habitualmente empregada na extinción de incendios, reduciu nun 86-100% a xerminación de sementes de *Lolium perenne* e *Agrostis tenuis* e inhibiu totalmente o seu enraizamiento. No entanto, o efecto negativo do polifosfato amónico sobre a vexetación desaparece a medio prazo (9-12 meses), de acordo cos resultados da experiencia de implantación de *P. pinaster* nas parcelas de campo, xa que o crecemento dos piñeiros en Q+P foi similar ao observado en NQ e maior que o rexistrado en Q, Q+E e Q+F, que non se diferenciaron entre si.

Ao contrario que para o N-NH_4^+, non se observaron variacións significativas na concentración de N-NO_3^- tras queima (Fig. III). Esta situación mantívose un mes despois, excepto para Q+P que, debido a unha nitrificación activa de parte das elevadas reservas de N-NH_4^+ (responsable da acidificación que sofre o solo de Q+P neste periodo), presenta uns niveis de N-NO_3^- maiores que nos restantes tratamentos. Tres meses despois do incendio observouse un incremento na concentración de N-NO_3^- en todos os tratamentos, o que indica un incremento da actividade dos microorganismos nitrificantes, favorecida pola maior humidade do solo no outono. Transcorrido un ano dende a queima prescrita, os niveis de N-NO_3^- foron similares en todos os tratamentos e comparables aos do inicio do experimento.

En comparación co observado durante o primeiro ano, o N-NH_4^+ e o N-NO_3^- aos 5 anos foron lixeiramente, pero non significativamente, menores. A longo prazo, o

over time (> 3 months), are features of high ecological significance for the post-fire vegetation recovery, as seed germination and seedling establishment can be inhibited by NH_4^+ toxicity (see BRITTO AND KRONZUCKER, 2002). In fact, in a greenhouse experiment with a burnt soil that received ammonium polyphosphate at the same dose as in the field, the germination of *Lolium multiflorum* and *Agrostis tenuis* seeds was reduced by 86-100% compared with the control burnt soil, and seedling establishment was completely inhibited (data not shown). However, in the medium-term the NH_4^+-N supplied by the ammonium polyphosphate could have a fertilizing effect.

The initial lack of significant differences among treatments in the NO_3^--N levels disappeared for BS+Ap between one and three months after the prescribed fire due to the active nitrification of its large NH_4^+-N pool, which is the cause of the significant soil acidification observed in the BS+Ap plots during this period (Fig. III). On the other hand, the general increase in the NO_3^--N concentration recorded at t=90 d in all soil treatments reflected a rise in the nitrifier microorganism activity, favoured by the higher soil humidity during the autumn. One year after prescribed burning, NO_3^--N levels were similar in all treatments and comparable to the beginning of the experiment.

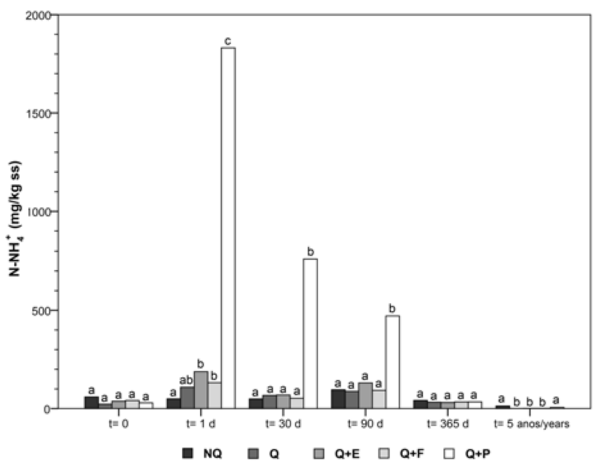

Fig. II. Evolución do contido en N-NH_4^+ do solo durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of NH_4^+-N content in the 0-2 cm soil layer along five years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

contido de N-NO_3^-, significativamente maior nas parcelas de NQ e Q+P, suxire unha maior nitrificación neta nestes solos.

A combustión provocou no tratamento de solo queimado sen adición de retardantes un incremento do P asimilable con respecto a NQ (Fig. IV), seguramente debido á forte mineralización de P orgánico polo lume (SAÁ et al., 1993), aínda que o efecto non resultou significativo. A adición de axentes retardantes de chama tampouco repercutiu no contido de P no solo, excepto no caso de Q+P no que o elevado aporte polo polifosfato amónico redundou nun enorme incremento deste nutriente en forma asimilable (70-140 veces maior que nos restantes tratamentos). Pese ao descenso continuado, os niveis de P asimilable en Q+P foron máis altos durante todo o estudo, e incluso despois dun ano continuaban sendo 10-20 veces superiores aos dos outros tratamentos, como tamén atoparon HOPMANS & BICKFORD (2003) inmediatamente despois da aplicación de Phos-Check. A persistencia a medio prazo duns niveis elevados de P adquire gran relevancia na recuperación da vexetación tralo lume xa que: a) en grandes cantidades, pode provocar problemas de antagonismo coa absorción de Fe e Zn na vexetación pioneira e dificultar o seu establecemento (MARSCHNER, 1995); e b) é un nutriente con frecuencia limitante nos ecosistemas naturais. Neste sentido, as perdas de nutrientes por lixiviado e/ou escorrentía e os procesos erosivos habitualmente observados en solos afectados por incendios (CHANDLER et al., 1983; CARBALLAS et al., 1993) poden contribuír de forma substancial ao risco de eutrofización das augas circundantes pola chegada masiva de P procedente das zonas queimadas que foron tratadas con retardantes ricos en P.

2. Efectos do lume e os retardantes sobre a vexetación

2.1. Concentración de nutrientes na vexetación aos 5 anos da queima

Os efectos do lume sobre o rendemento, o crecemento e o nivel de cobertura das distintas especies de mato foron avaliadas por varios autores (LARSON et al., 2000; BELL et al., 2005; CRUZ et al., 2005), con todo, o estado de nutricional está moi pouco estudado.

The increment in available P in BS compared with US (Fig. IV) was probably due to the strong mineralizing effect of fire on organic P (SAÁ et al., 1993), although in our case differences did not reach significant levels. No

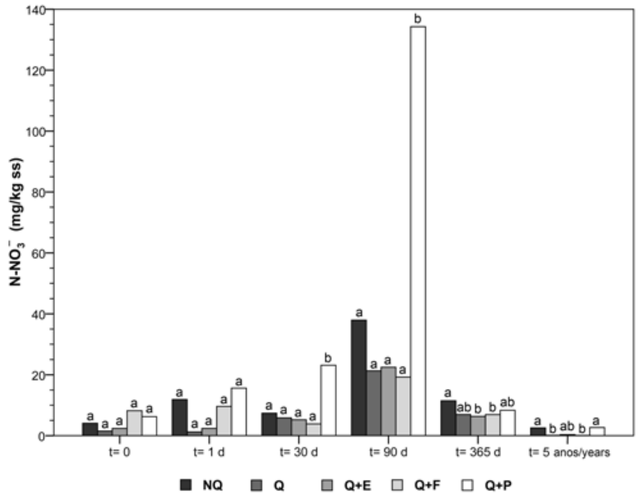

Fig. III. Evolución do contido en N-NO_3^- do solo durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of NO_3^-N content in the 0-2 cm soil layer along five years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

fire fighting chemical had any influence on available P except ammonium polyphosphate, which provoked an increment in soil P levels that remained significantly higher (10-20 times) than for the other treatments, even one year after the fire as also found HOPMANS AND BICKFORD (2003) for the application of Phos-Check. The medium-term (1 year) persistence of high P levels may acquire great importance for the post-fire vegetation recovery as: a) at high levels, P could have an antagonistic effect on Fe and Zn plant uptake (MARSCHNER, 1995); and b) P is a common limiting nutrient. Moreover, the enhanced nutrient losses due to leaching and erosion that have habitually been reported in soils affected by wildfires (CHANDLER et al., 1983; CARBALLAS et al., 1993) may increase risks of water eutrophication due to higher soil P outputs from the burnt soils treated with P-rich fire fighting chemicals.

O efecto do factor especie sobre o contido en N total (que é máximo en *U. micranthus* e *P. tridentatum* (Fig. V)) explícase pola simbiose das leguminosas con microorganismos fixadores de N_2 atmosférico. En canto ao factor tratamento, apréciase un efecto negativo e significativo da queima só no caso de *E. umbellata* e un efecto positivo da aplicación de polifosfato amónico en todas as especies, que non alcanza valores significativos en *P. tridentatum* e *P. pinaster*.

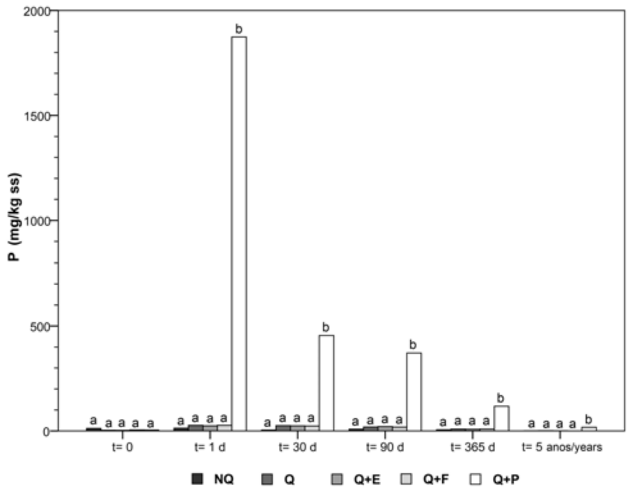

Fig. IV. Evolución do contido en P asimilable do solo durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of available P content in the 0-2 cm soil layer along five years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

O ^{15}N tamén separa as especies leguminosas das non leguminosas (Fig. VI). As leguminosas sitúanse nun rango moi estreito, próximo á abundancia natural e inferior ao $\delta^{15}N$ do solo (valores medios de -0,45 ‰ en *U. micranthus* y -0,04 ‰ en *P. tridentatum*); o primeiro suxire unha fonte maioritaria de N común e o segundo apunta a que esa fonte podería ser o N_2 atmosférico (véxase SHEARER & KOHL, 1993).

Pola súa banda, as non leguminosas mostran valores máis variables aínda que sempre claramente negativos, excepto os piñeiros de Q+P. En *E. umbellata*, o valor moi negativo das plantas desenvolvidas en NQ indica que, como outras ericáceas, esta especie establece asociacións con micorrizas que lle aportan boa parte dos seus requerimientos de N (HOBBIE E HOBBIE, 2008); o forte fraccionamiento isotópico na transferencia de N do simbionte ao hospedador sería, pois, responsable de que o $\delta^{15}N$ na planta sexa un 4-5 ‰ inferior ao do solo. O

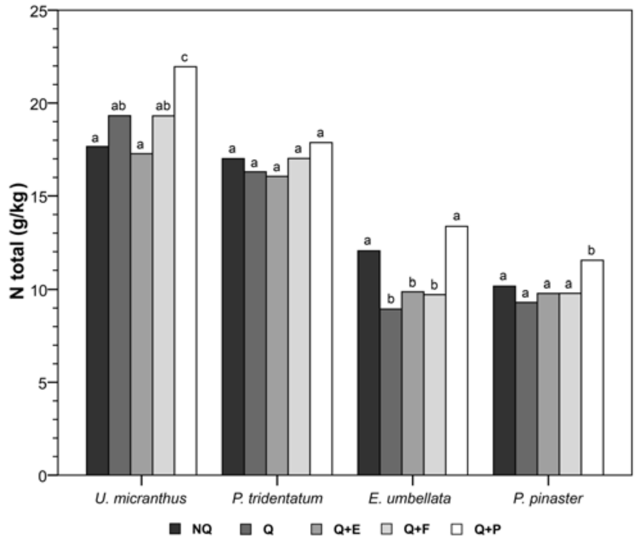

Fig. V. Contido en N do material foliar do mato de rexeneración natural (*U. micranthus, P. tridentatum* e *E. umbellata*) e os *P. pinaster* de reforestación.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Total N concentration in foliar materials (*U. micranthus, P. tridentatum, E. umbellata* and *P. pinaster*) 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

2. Effects of fire and fire-fighting chemicals on the vegetation

2.1. Effects of fire and fire-fighting chemicals on plant nutrient concentrations

Although the important effects of FFCs on streams and aquatic organisms are a cause of major concern, few research has evaluated their impact on terrestrial vegetation (GIMÉNEZ et al., 2004). The effects on yield, growth and coverage level of different species were assessed by several authors (LARSON et al., 2000; BELL et al., 2005; CRUZ et al., 2005), but plant nutrition status has not been studied.

The higher total N concentration (in *U. micranthus* and *P. tridentatum* (Fig. V)) was explained by the symbiosis of legumes with atmospheric N_2-fixing microorganisms, while differences among treatments showed a negative effect of burning only in *E. umbellata* and a positive effect of the application of ammonium polyphosphate in all species.

Legumes $\delta^{15}N$ values suggested a common major N source, close to natural abundance and below soil $\delta^{15}N$, that might be atmospheric N_2 (see SHEARER AND KOHL, 1993 (Fig. VI)).

The very negative $\delta^{15}N$ values of *E. umbellata* plants growing in US suggested that, like in other ericaceous species, mycorrhizal associations provided much of its N factor tratamento revela dous efectos claros sobre o δ ^{15}N en Erica: a) os valores 0,5 ‰ máis negativos en Q, Q+E e Q+F respecto de NQ suxiren que esta especie depende en maior medida do N aportado polas micorrizas debido a que a dispoñibilidade de N no solo é menor (como tamén indican os valores de %N en planta) e b) o valor un 2 ‰ máis alto observado en Q+P suxire unha menor dependencia do N aportado polas micorrizas, ben porque a dispoñibilidade de N sexa maior polo efecto fertilizante do polifosfato amónico, ben por un posible efecto tóxico deste retardante sobre as micorrizas. En Pinus, os valores de δ ^{15}N seguen unha tendencia moi similar á observada en Erica aínda que en promedio un 1,5-2 ‰ máis positivos.

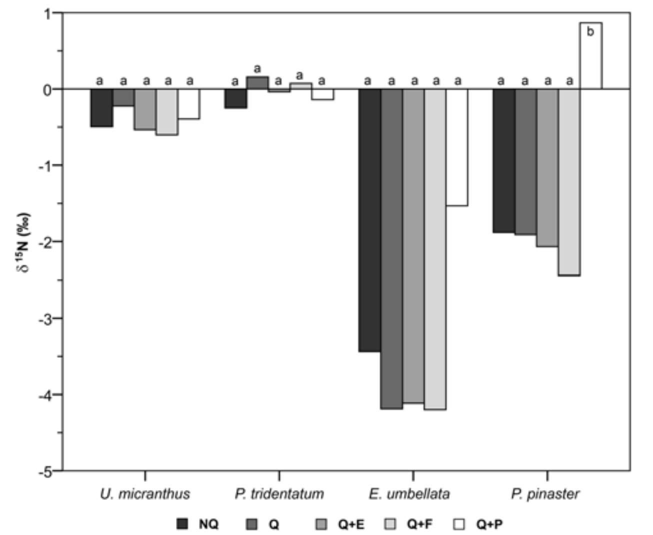

Fig. VI. Abundancia natural de δ ^{15}N no material foliar do mato de rexeneración natural (*U. micranthus, P. tridentatum* e *E. umbellata*) e os *P. pinaster* de reforestación. NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
δ ^{15}N in foliar materials (*U. micranthus, P. tridentatum, E. umbellata* and *P. pinaster*) 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium

Os niveis foliares de P nas plantas das parcelas de NQ e Q, en contraste cos resultados de BROCKWAY et al. (2002), revelaron a ausencia de efectos do lume a longo prazo sobre esta variable. Pola contra, as concentracións foliares de P, significativamente máis altas en todas as plantas cultivadas en parcelas Q+P, está en consonancia cos resultados no solo e ambos son unha consecuencia a longo prazo do P aportado polo retardante.

requirements (HOBBIE AND HOBBIE, 2008); the strong isotopic fractionation in the N transfer from the symbiont to the host would led to plant δ ^{15}N 4-5 ‰ lower than that of the soil. Two clear impacts of treatment on *E. umbellata* δ ^{15}N were found: a) the 0.5 ‰ more negative values in BS, BS+Fo and BS+Fi respect to US suggested that this species is more dependent on N supplied by mycorrhiza because of lower soil N availability (as also indicated by plant N concentration); and b) the 2-2.5 ‰ higher values in BS+Ap suggested lesser dependence on mycorrhizal N supply, either by increased N availability because of the previously discussed fertilizer effect or by a toxic effect of this FFC on mycorrhiza. In Pinus, probably due to their ectomycorrhizal associations, δ ^{15}N values followed a similar trend to that observed for *E. umbellata* although, on average 1.5-2 ‰ more positive.

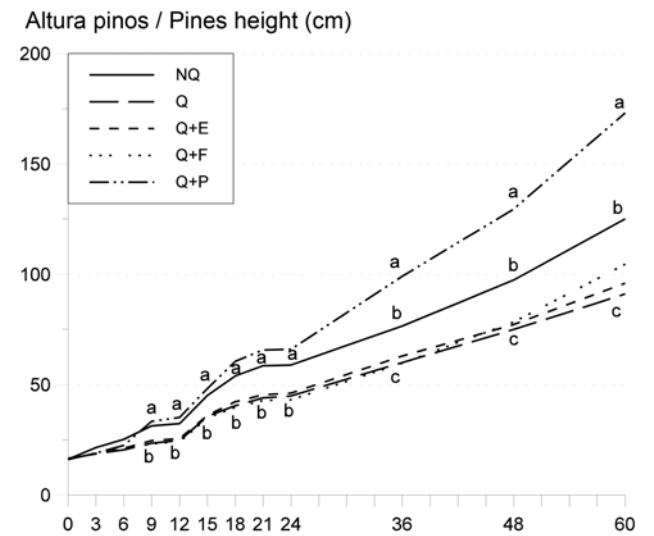

Fig. VII. Evolución da altura de *P. pinaster* de reforestación durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of *P. pinaster* height during the first 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

The similar foliar P level in plants from US and BS plots contrasted with the results of Brockway et al. (2002) and showed a lack of any long term effect of fire on this variable. On the contrary, the significantly higher foliar P concentration in all plants grown on BS+Ap plots coincided with the similar result in soils and both were a long-lasting consequence of P supplied by the ammonium polyphosphate FFC.

2.2. Cuberta vexetal

A evolución das plántulas de *P. pinaster* mostrou tres patróns distintos (Figs VII-VIII): a) árbores das parcelas de NQ que presentan a menor mortandade e maior altura (pero non diámetro basal) que as árbores das parcelas Q, Q+F e Q+E ao longo de todo o período de estudo,
b) árbores das parcelas Q+P, cun crecemento inicial (0-6 meses) máis lento que os de NQ, pero que, despois de 2-3 anos, convertéronse nos máis grandes aínda que coa segunda maior mortandade, e c) as árbores das parcelas Q, Q+F e Q+E, coas menores taxas de crecemento e mortandade intermedia (excepto os de Q+F que presentan a mortandade máis alta).

En canto á rexeneración natural da cuberta vexetal (Fig. IX), ao cabo de 5 anos tanto nas parcelas queimadas coma nas non queimadas existen 4 especies dominantes: *U. europaeus, U. micranthus, E. umbellata* e *P. tridentatum*. *E. umbellata* é a especie con maior cobertura (> 85 %) en todos os tratamentos, excepto Q+P, que difire significativamente do resto e onde a mencionada especie ocupa arrededor da metade de superficie (~ 40 %). A porcentaxe de solo cuberto por leguminosas foi significativamente maior nas parcelas Q+P que nos outros tratamentos; como vimos, o contrario sucedeu con *E. umbellata*, probablemente porque é unha especie que se rexenera exclusivamente a partir de semente (REYES et al., 2009), e este resultado débese probablemente ao ben documentado efecto negativo do polifosfato de amonio na xerminación e a viabilidade de sementes (LUNA et al., 2007). No referido á altura (Fig. X), todas as especies comparten dúas características: son significativamente máis altas en Q+P e o tamaño acadado no resto de tratamentos (entre 44 y 55 cm) é moi similar.

O bo desenvolvemento da vexetación nas parcelas Q+P, a partir do segundo ano despois de queima, puxo de manifesto que os fortes efectos negativos a curto prazo do polifosfato de amonio sobre a viabilidade das sementes, a xerminación e establecemento de plántulas (CRUZ et al., 2005; LUNA et al., 2007) poden desaparecer na natureza unha vez que o retardante se elimina, como así se indica para as taxas de aplicación normal (ANGELER et al., 2004). Tanto a rexeneración natural do mato como o crecemento das árbores mostrou que o polifosfato tivo

2.2. Effects of fire and fire-fighting chemicals on vegetation cover

The evolution of the planted *P. pinaster* seedlings showed three distinct patterns (Figs VII-VIII): a) trees in US plots with the lowest mortality and higher height, but not basal diameters, than trees from BS, BS+Fi and BS+Fo plots along the whole study; b) trees from BS+Ap plots, that grow slower than those from US during the first 6 months and, became the biggest after 2-3 years, but with the second highest mortality; and c) trees from BS, BS+Fi and BS+Fo plots with the lowest growth rates, and intermediate mortalities (except those from BS+Fi with the highest one).

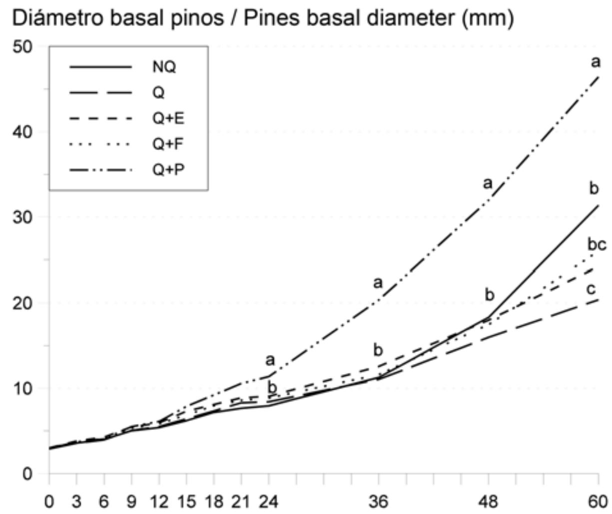

Fig. VIII. Evolución do diámetro basal de *P. pinaster* de reforestación durante os 5 anos de estudo.
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Evolution of *P. pinaster* basal diameter during the first 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

Five years after the prescribed fire both burnt and unburnt plots presented 3 common dominant shrub species: *Ulex micranthus, Pterospartum tridentatum* and *Erica umbellata*; a fourth dominant species, *Ulex europaeus*, was also present in the BS and BS+Ap treatments (Figs. IX-X). The percentage of soil covered by legumes was significantly higher in BS+Ap plots than in the other treatments; the reverse was true for *E. umbellata*, the only one of these species that regenerates exclusively from seeds (REYES et al., 2009). This result was likely due to the well documented negative effect of ammonium polyphosphate on seed germination and viability (LUNA et al., 2007).

un efecto fertilizante a longo prazo que favoreceu o crecemento da vexetación, resultando nun aumento da cobertura e o tamaño xeral de todas as especies. Este resultado concorda cos de LARSON & DUNCAN (1982), que observaron como unha zona de pastizais queimados que recibiran un retardante de fosfato diamónico produciu o dobre que a zona control non queimada durante polo menos dous anos; BELL et al. (2005) atoparon que o efecto fertilizante dun retardante fosfatado favorecía que medraran os brotes das especies clave consideradas, aínda que non aumentaba significativamente a altura total destas especies. Con todo, é importante destacar tres motivos de preocupación que xorden no noso estudo debidos ao uso de polifosfato amónico: a) foi o segundo retardante que causou maiores perturbacións nas comunidades microbianas do solo no longo prazo (BARREIRO et al., 2010); b) a moi baixa cobertura de *E. umbellata* nas parcelas Q+P (entre 40-50% dos outros tratamentos) demostrou que ata nos ecosistemas mesotróficos algunhas especies poden ser desprazadas por outras favorecidas polo efecto fertilizante dos retardantes, proceso que pode ser máis perxudicial no caso de especies sensibles ou ecosistemas oligotróficos, e c) Q+P foi o segundo tratamento con maior porcentaxe de piñeiros mortos.

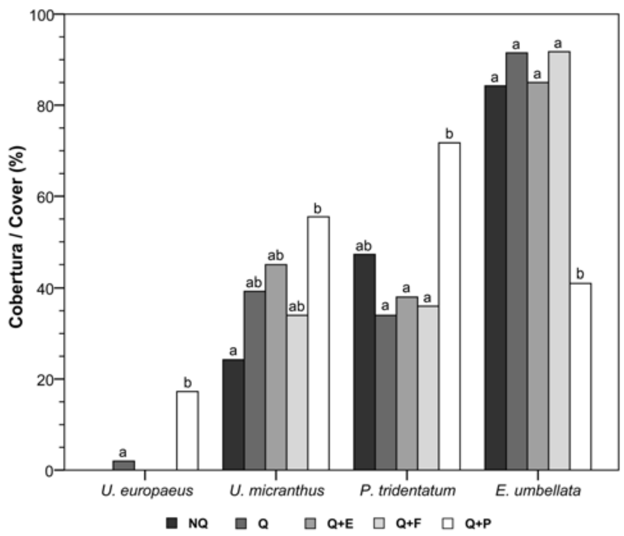

Fig. IX. Cobertura das catro especies dominantes no mato de rexeneración natural (*U. micranthus, P. tridentatum* e *E. umbellata*).
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Shrub cover 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

Os toxos (*Ulex spp.*), pola súa característica ecolóxica de rebrote a partir de cepa, parece que non sofren o efecto

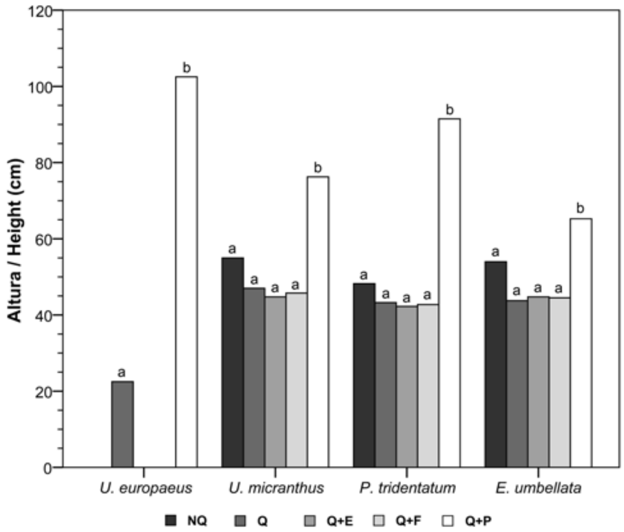

Fig. X. Altura das catro especies dominantes no mato de rexeneración natural (*U. micranthus, P. tridentatum* e *E. umbellata*).
NQ, non queimado; Q, queimado; Q+E, queimado máis escumante; Q+F, queimado máis Firesorb; Q+P, queimado máis polifosfato amónico.
Shrub height 5 years after the prescribed fire.
NQ, unburnt soil; Q, burnt soil; Q + E, burnt soil + foam agent; Q + F, burnt soil + Firesorb; Q + P, burnt soil + ammonium polyphosphate.

The good vegetation development in BS+Ap plots from the second year after the fire showed that the short-term strong negative effects of ammonium polyphosphate on seed viability, germination and seedling establishment (CRUZ et al., 2005; LUNA et al., 2007) may have disappeared in nature once the retardant was eliminated, as reported for normal application rates (ANGELER et al., 2004). Both the natural regeneration of scrubs and the growth of planted trees showed that ammonium polyphosphate had a long-term fertilizing effect that enhanced vegetation growth, resulting in an increased soil coverage and overall size for most species. This result agreed with those of LARSON AND DUNCAN (1982) who reported that a grassland burned area that received a di-ammonium phosphate FFC yielded twice as much as the unburned control area during at least two years. Our results also agreed partially with those of BELL et al. (2005) who found that the fertilizing effect of a P-bearing FFC generally increased shoot growth of the key species considered, but did not significantly increase the overall height of these species. However, it must be highlighted that three causes of concern arose on the use of ammonium polyphosphate FFCs: a) it was the FFC with the second highest effect on the soil microbial communities at the long-term (BARREIRO et al., 2010); b) the very low *E. umbellata* cover in BS+AP plots (only 40-50% of deletéreo a curto prazo do polifosfato amónico sobre sementes e plántulas e vense moi favorecidos polo efecto fertilizante a medio-longo prazo, o que se traduce nunha vexetación co maior porte e cobertura; posto que son leguminosas fixadoras de N_2 atmosférico, o efecto fertilizante do polifosfato amónico probablemente se deba ao gran aporte de P (AUGUSTO et al., 2005). A maior cobertura de *E. umbellata* nas parcelas NQ concorda coa característica de rexeneración a partir de semente desta especie; no proceso de sucesión secundaria tras o incendio a estratexia reprodutiva de *E. umbellata* promove que nas parcelas queimadas a recuperación sexa máis lenta, aínda que máis estable a longo prazo, fronte a especies rebrotadoras como *U. micranthus*. Parece que a queima inflúe negativamente no rebrote de *P. tridentatum*. Posto que a cobertura de *P. tridentatum* nas parcelas queimadas (excepto Q+P) é menor que en NQ, aínda que non de forma significativa, parece indicar que o lume exerce unha influencia negativa sobre a devandita especie; este resultado contrasta co atopado por REYES et al. (2009) quen sitúan a este especie entre os rebrotadores fortes.

that on the other treatments) showed that even in mesotrophic ecosystems some species can be displaced by others favoured by the fertilizing effect of these FFCs, a process that can be worse in the case of sensitive oligotrophic species or ecosystems; and c) BS+Ap was the second treatment with highest *P. pinaster* mortality.

Gorse (*Ulex spp.*), characteristically regrowing from stumps, seemed not to suffer the short-term deleterious effect of ammonium polyphosphate on seeds and their seedlings, and was greatly favoured by the fertilizing effect in the medium- to long-term which resulted in the largest vegetation size and coverage. As gorse is a N_2-fixing legume, the ammonium polyphosphate fertilizer effect was likely due to the great contribution of P (AUGUSTO et al., 2005). The lesser coverage of *E. umbellata* in burnt plots agreed with its regeneration exclusively from seed that, during the secondary succession after fire, led to slower recovery than strongly re-sprouting species like *Ulex spp.* (REYES et al., 2009). Although *P. tridentatum* is a strong resprouter (REYES et al., 2009), the results suggested that, at least in the studied case, burning have had a negative impact on its germination or regrowth.

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