The irruption of new agro-industrial technologies in Uruguay and their environmental impacts on soil, water supply and biodiversity: a review

Carlos Céspedes-Payret

UNCIEP (Unidad de Ciencias de Epigénesis),
Facultad de Ciencias, Universidad de la República,
Igua 4225, C.P. 11.400 Montevideo, Uruguay
Email: cespedes@fcien.edu.uy

Gustavo Piñeiro

Instituto de Ciencias Geológicas,
Facultad de Ciencias, Universidad de la República,
Igua 4225, C.P. 11.400 Montevideo, Uruguay
Email: gaitapi@fcien.edu.uy

Marcel Achkar

Lab. de Desarrollo Sustentable y Gestión Ambiental del
Territorio del Departamento de Geografía,
Facultad de Ciencias, Universidad de la República,
Igua 4225, C.P. 11.400 Montevideo, Uruguay
Email: achkar@fcien.edu.uy

Ofelia Gutiérrez and Daniel Panario*

UNCIEP (Unidad de Ciencias de Epigénesis),
Facultad de Ciencias, Universidad de la República,
Igua 4225, C.P. 11.400 Montevideo, Uruguay
Email: oguti@fcien.edu.uy Email: gutierrez.ofelia@gmail.com
Email: panari@fcien.edu.uy Email: daniel.panario@gmail.com
*Corresponding author

Abstract: In recent years, economic growth has produced a global change in the demand for food, fibre and energy supply. This has gone together with the globalisation of the agro-industrial production systems, leading to a qualitative change in land use because of intensive use of technological inputs. Uruguay, just as the other countries of the region, is part of this phenomenon. The massive introduction of forest crops has been made over native grassland ecosystems, replacing traditional productive activities of the post-colonial period. Research on eucalyptus afforestation shows depletion of the ecosystem services associated with grassland and loss of the resilience capacity of the system. Impacts on soil organic matter, soil physicochemical properties, the hydrological cycle and on biodiversity are analysed. This review (with emphasis on Uruguay and the River Plata Basin) tries to contribute to an integrated vision of the environmental consequences of current land-use change.

Keywords: agro-industrial; land-use change; forest crops; grassland ecosystems; eucalyptus afforestation; ecosystem services; environmental; impacts on soil; hydrological cycle; glyphosate; biodiversity; Uruguay; River Plata Basin; environment and health.

Reference to this paper should be made as follows: Céspedes-Payret, C., Piñeiro, G., Achkar, M., Gutiérrez, O. and Panario, D. (2009) 'The irruption of new agro-industrial technologies in Uruguay and their environmental impacts on soil, water supply and biodiversity: a review', *Int. J. Environment and Health*, Vol. 3, No. 2, pp.175–197.

Biographical notes: Carlos Céspedes-Payret is a Biologist. He received his PhD in Agronomical Sciences from the Institut National Polytechnique de Toulouse, France, and his MSc in Environmental Sciences from the Universidad de la República, Uruguay. His main research interests focus on afforestation impacts on soils and other environmental impacts. He is Assistant Professor of the UNCIEP (Epigenesis Sciences Unit), Faculty of Science of the Universidad de la República, Uruguay.

Gustavo Piñeiro is a Geologist. He is an Assistant Professor in the Department of Evolution of Sedimentary Basins and Environmental Geology, Faculty of Science of the Universidad de la República, Uruguay. His main research interests focus on natural resources management and environmental geology.

Marcel Achkar is a Geographer. He received his PhD in Agronomical Sciences from the Institut National Polytechnique of Toulouse, France, and his MSc in Environmental Sciences from the Universidad de la República, Uruguay. He is an Associate Professor at the Laboratory of Environmental Management and Sustainable Development of Land, Faculty of Science of the Universidad de la República, Uruguay. His main research interests focus on land-use planning and sustainable development working with remote sensing techniques.

Ofelia Gutiérrez is a Geographer. She is Assistant Professor of the UNCIEP (Epigenesis Sciences Unit), Faculty of Science of the Universidad de la República, Uruguay. She is the author or co-author of more than 30 technical-scientific publications on environmental topics, physical geography and environmental impacts assessment, including articles in international journals, books and chapters of books.

Daniel Panario is a Professor of Geomorphology, Director of the UNCIEP (Epigenesis Sciences Unit) and Coordinator of the Master of Environmental Science, at the Faculty of Science of the Universidad de la República, Uruguay. He is the author or co-author of about 90 scientific publications, including articles in international journals, books and chapters of books and papers in national and international conference proceedings. His research interests include fields such as environmental topics, physical geography, natural resources and edaphology.

1 Introduction

In recent years, a fundamental change has been promoted within the global agricultural sector, owing to biotechnological and agro-industrial development (Duarte et al., 2006; McAfee, 2008). Unlike the *Green Revolution*, this sector conversion has focused on the fast expansion of a very small variety of cultivars, mainly clones and/or transgenic ones (soybean, rice, cotton, maize and eucalyptus) associated with an intensive use of agrochemicals and large productive units.

In the case of eucalyptus afforestation, the production of pulp for paper has been one of the economic objectives that have determined its expansion. This phenomenon has been associated with the migration of the pulp agro-industrial chain from the countries of the northern to those of the southern hemisphere (Altesor et al., 2008) due to comparative advantages (lower environmental requirements, higher yields, greater availability of raw material and appropriate soils, permissive tax concessions, among others). This is the case of business ventures like Botnia/Metsalito (Finland), ENCE (Spain), Weyerhaeuser (USA), Stora Enso (Sweden/Finland), Portucel Soporcel (Portugal) and others that have been established in Uruguay.

The controversy over the environmental risks and benefits of adopting genetically engineered organisms is polarised around pro and anti-biotechnology groups, but the current level of knowledge is frequently overlooked in this debate. A review of existing scientific literature reveals that environmental risks and benefits are not sufficiently taken into account (Wolfenbarger and Phifer, 2000; Panario, 2001; Reichenberger et al., 2007; Bale et al., 2008).

However, the risks not only result from the use of these transgenic crops but also from management associated to this new type of agriculture (Kumar et al., 2008). In the case of eucalyptus plantations – being a permanent crop composed of fast-growing tree species or clones – their environmental impacts are directly associated with their commercial purposes (van Dijk and Keenan, 2007). These objectives determine the type of management of this plantation, its density (number of trees per land unit area) and turn (time between harvests), which are usually short (under 10 years). In the case of higher density and shorter turns, the expected environmental impact will be potentially greater, particularly on the soil.

The current productive reorganisation of the territory has also implied the displacement of traditional rural activities – such as cattle raising or the production of grains and oilseed crops – towards less productive lands or a drastic reduction in their extension causing rural migration and loss of food safety. These displaced productive items had evolved in the country since the post-colonial time and strengthened after 1870, when in Uruguay wire fencing of the country was decided.

At present, in Uruguay, there are almost one million hectares of tree plantations, mostly composed of eucalyptus and pine trees. Within that area, some 500,000 hectares are controlled by three of the above-mentioned transnational corporations (Redes, 2008).

Expansion processes of tree plantations and the associated concentration of land property, have gone hand in hand, and are directly related to the late 1980s new Forestry Law. Through this law, the State promoted afforestation in an articulated way with the private export sector, including a number of benefits such as economic and financial incentives.

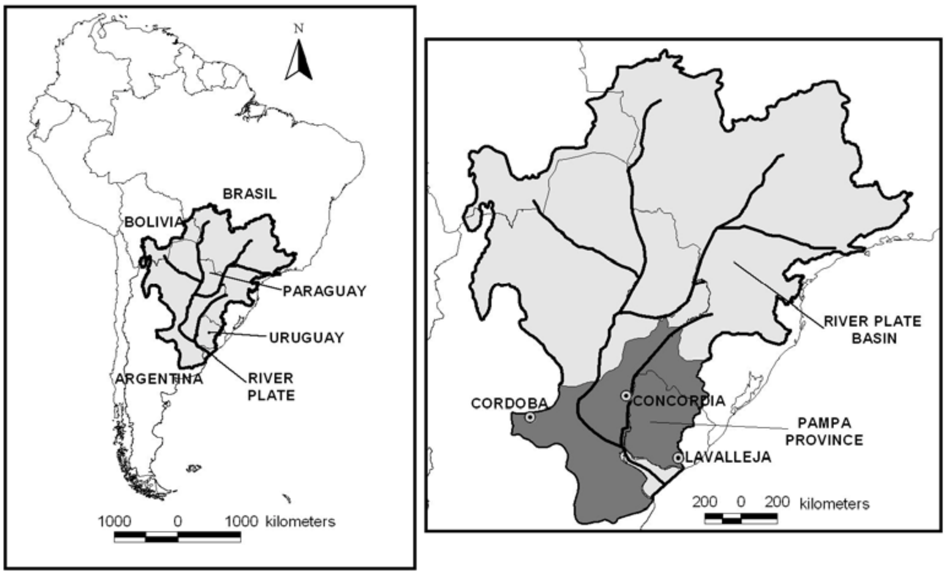
Since its inception, the forestry project was mainly defined for the production of raw material for the pulp and paper industry – from eucalyptus wood – which was reflected in the species composition of plantations undertaken since the early years of its implementation.

Capital investments from the forestry sector have been sufficiently strong to make decision makers minimise the associated social, economic and ecosystem negative impacts. In part, this is justified by the recurrent denial (and in some cases because of ignorance) of the environmental costs (or liabilities) due to the effects on ecosystem services given by productive activities from the use of natural resources (Panario and Gutiérrez, 2007). As a result, the State has only evaluated the benefits of the forestry activity on the Gross Domestic Product (GDP) and the Balance of Payments, but has not taken into account the externalities associated with the gradual loss of ecosystem services (environmental liability). These services, which are not valued nor regulated by the market, are vital for human society: clean water, runoff control, aquifers recharge, biological control of plagues, conservation of biodiversity, carbon accumulation or the retention of polluting agents, among many other services (e.g. Alexander et al., 1997; Daily et al., 1997; Bishop and Landel-Mills, 2002; De Groot et al., 2002). Nevertheless, according to Costanza et al. (1997), the economic global value of services without a market price may exceed the GDP of a country.

2 Land use/land change in the Rio de la Plata Basin

As in great part of the River Plata Basin, grassland vegetation in Uruguay is part of the so-named Pampa Province (Cabrera and Willink, 1973; Morrone, 2001; Morrone, 2006), more specifically the Uruguayense District (Cabrera, 1971; Cabrera and Willink, 1973; Cabrera, 1976) (Figure 1). This district covers an area of about 400,000 km^2, which includes most of the Uruguayan territory, the south of Brazil and part of the eastern region of Argentina. In Uruguay, this surface represents almost 80% of its territory and includes vegetation communities of a great diversity of species (~2000) predominantly herbaceous.

Figure 1 Location of the reference zone. Light grey indicates the limits of the River Plate Basin. In the figure on the right, dark grey shows the limits of the Pampa Province (Cabrera and Willink, 1973; Morrone, 2001; Morrone, 2006)



The state of preservation of the pampas grasslands and the soil associated to these has declined because of the historical development of cattle raising (Panario and Bidegain, 1997; Altesor et al., 1998) and agriculture in the Rio de la Plata Basin. In the last decades, this generalised process of deterioration has been increased with the advance of the soybean and eucalyptus crops. Thus, according to Paruelo et al. (2006) the expansion of soybean in Argentina and afforestation in Uruguay are two of the most important transformations happened in the grasslands of the Rio de la Plata. These facts are part of a broader and previously existing phenomenon: the 'agriculturisation' of the extensive productive systems. This phenomenon does not happen only in Uruguayan and Argentinean territory, but it is also seen in other countries of South America, such as Bolivia, Brazil and Paraguay (Eva et al., 2004; Paruelo et al., 2004). The 'agriculturisation' is a particular (and frequent) case of change in the land use, where the alteration of the vegetation cover constitutes one of the principal dimensions of the phenomenon known as 'Global Change'. Together with climate alterations and changes in the atmosphere composition, the change in the land use has environmental consequences which exceed the local or regional limits and are stated in a global scale (Duarte et al., 2006; Paruelo et al., 2006).

In the matter, there is an increasing number of evidences which show the consequences of the agricultural expansion on the climate, the carbon (Houghton, 2001; Lal, 2005) and the nitrogen balance, the emissions of trace gases with greenhouse effect, the biodiversity and the hydric balance (Houghton, 2001).

We must emphasise that the current land-use change is accompanied by a technological qualitative change given by the intensive use of input (energy, machinery, fertilisers and pesticides).

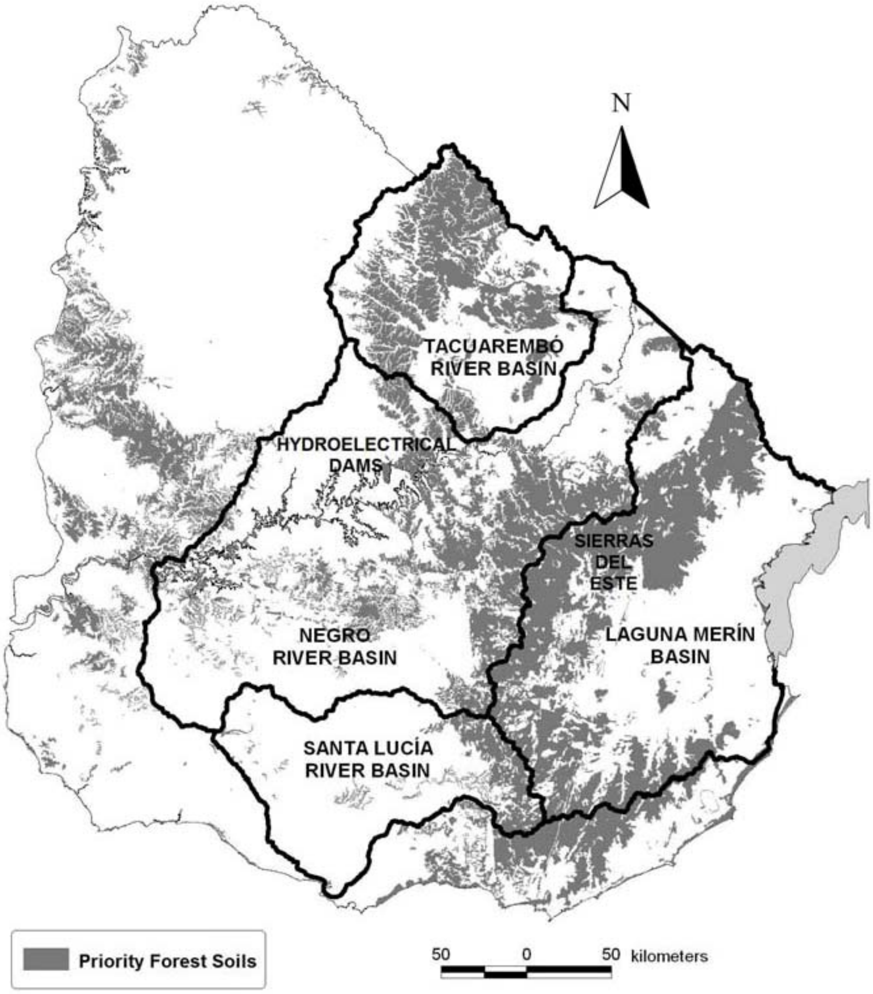
3 Uruguay: afforestation and land-use change

The drastic change of land use in Uruguay relies on the Forest Law (No. 15.939 of the 28/12/1987), its principal stage. Implemented through the Forest National Plan in 1991, this law anticipated a series of economic and financial benefits (tax exemption, partial reimbursement of costs, special credit lines and exemption from custom fees). To complement these decisions companies under 'corporation' were allowed to acquire land when their main use was forestry.

Moreover, the law provided a definition and delimitation of 'soils of forest priority' (Figure 2). However, the law did not disable afforestation activities in other type of soils, so it is estimated that 23% of industrial plantations are mostly in fertile soils appropriated for other activities such as food agriculture. This percentage comes from an analysis of Landsat satellite 2007 images, compared with mapping units of 'soils of forest priority'.

The impulse given by the multilateral cooperation and credit agencies to the forest sector was accompanied by a conceptual distortion. That is, assigning the same attributes and benefits of natural forests to afforestation: erosion control, fertility restoration, climate regulation, regulation of river flows and maintenance of the ecological balance, among others. Based on this confusion, promoters will then determine in which areas of the country this activity would be convenient (Panario and Gutiérrez, 2007). This way, a fallacious association arises: soils of forest priority are relatively sandy soils, well drained, with medium or low fertility and productivity for meat or wool, and therefore are 'little productive' for a country based on a heavy livestock economy. Nevertheless, this association of ideas ignores that they are really the most productive soils for summer crops (maize, citrus), horticulture (cucurbits) among others. But it mainly ignores the hydrologic connectivity and the contribution of high basins to ecological integrity at regional scale (Freeman et al., 2007) and that they are also the most important areas for the production of runoff water useful for other productive uses.

Figure 2 Dark grey indicates the distribution of 'priority forest soils' in relation to watersheds of greater socio-economic importance in Uruguay: Santa Lucia River Basin which supplies drinking water to over 60% of the urban population of the country; both Tacuarembó River and Negro River Basins provide the hydroelectric dams that produce 39% of hydropower generation and Laguna Merín Basin which is the main basin of irrigation for rice crops and wetlands enrolled in the RAMSAR Convention



From a farming total surface of more than 16,000,000 ha (MGAP-DIEA, 2009), the soils declared as of forestry priority by Law 15.939 (28/12/1987), occupied a surface of near 3,600,000 ha. But through 2006 (191/06 y 220/06) regulation decree, they have increased in approximately 400,000 ha. This modification – closely related to the arrival of new investors – leads to a situation where the surface originally included in Law 13.723 (16/12/1968), turns from the 11% to the 25% of the farming surface of the country, which means more than the double of the original one.

In this political decision the underlying idea is that the whole of these lands have a medium or low productivity in relation to other farming uses, but they have a common high potential for tree plantation. They are, in general, sandy soils, sandy-clayey or/and with rocky or stony outcrops, distributed in different zones and cartographied in a detailed level by CONEAT (1979) (See Figure 2).

Nevertheless, we should take into account that not all the 'forestry priority' soils are equally appropriate for the growing of some eucalyptus species, particularly, for those species with a greater demand of nutrients, as those assigned for pulp industry (*Eucalyptus globulus* and *E. grandis*). Due to low fertility, frost, deficient drainage and other elements, many of these soils are not suitable for eucalyptus or may not be profitable for commercial purposes.

Eucalyptus has a greater demand of humidity than grassland ecosystems. As they are introduced by replacing grasslands, they will release a minor surplus of water, which will be expressed through the net performance of the hydrographical basin and the available water from the recharge of the phreatic layers (Nossetto et al., 2005). This way, changes on the hydrological cycle will be expected when in a basin we introduce a high-density fast-growing tree plantation covering a significant area of its high slopes.

Current trends show a wide spreading of *E. globulus* plantations towards the east of the country because of comparative advantages, essentially climate and sanitary ones. This species is expected to be almost exclusively for the pulp production purpose (just as 50% of the plantations of *E. grandis*) for the next years. The reference zone is the Laguna Merin basin and the high basin of Santa Lucía River, where – as anticipated – Portucel Company will set up. This zone represents the source of the waterway drainage for irrigation and drinkable water purposes respectively. At the same time, northern and northeast soils are located in the principal hydroelectrical dam system of the country (See Figure 2).

4 Afforestation and environmental impacts on grassland soils

4.1 Grassland and soil organic matter

The scientific literature review shows the importance of grassland soil organic matter as a first-order issue in the analysis and understanding of the scope of the impacts of the conversion of grasslands to fast-growing forest crops.

Soils are the main carbon sink, as they accumulate 75% of the total organic carbon of the earth (Henderson, 1995; Paustian et al., 2000). Accordingly, a change in land use can exert a strong influence on its reservoir, even in a time scale of decades or centuries. This has aroused the interest of scientists, particularly from the commitments made by countries in the agreements on climate change. However, agreements such as Kyoto Protocol only recognise - as mitigation activities in CO_2 emissions - to those promoted by humans, such as forestry activities. Thus, there is a change in the way of thinking land use and land cover. These mitigation proposals could determine that the current agricultural production systems became part of a new market, the market for the sale of 'environmental services' as carbon sinks.

This new proposal for the global agricultural sector could be accepted without objections, but these programmes, in many cases, promote the substitution of native vegetation. This is the case of the replacement of natural grasslands by fast-growing trees. However, under this new conception of land use, the role of soil carbon in the global balance of this element has not been properly taken into account.

4.1.1 C-sink and grassland soil

Among the whole soil properties potentially affected by the progress of afforestation, the native reserve of organic matter is a *key factor* since a change in content and/or quality affects directly or indirectly on other edaphic parameters (e.g. Huntington et al., 1989; McBride, 1994; Sikora and Stott, 1996; Seybold et al., 1997; Povirk et al., 2001; Maquere et al., 2008). Thus, in the case of South American grasslands, the introduction of eucalyptus afforestation has resulted in a significant reduction of the accumulated organic matter in the grassland soil (e.g. Jackson et al., 2002; Carrasco-Letelier et al., 2004; Jobbágy et al., 2006; Céspedes-Payret, 2007). At the beginning, this loss can be explained, through the effects of the soil tillage and herbicide application during the early stages of the crops development (Paul et al., 2002).

After afforestation there are qualitative and quantitative changes in the soil organic matter, its turnover and spatial distribution (Paul et al., 2002; Céspedes-Payret, 2007). There are also drastic changes in soil biota microorganisms after the land-use change. The cultivation of eucalyptus is supposed to be the beginning of existing grassland carbon mineralisation (C_{C4} in afforested soils of Uruguay) and of the synthesis and mineralisation of soil organic matter (C_{C3}) under eucalyptus. Surveys which have analysed the isotopic relation based on $\delta\ ^{13}C$ have estimated the residence average time of both carbon fractions (Six and Jastrow, 2002). The results show a strong initial fall of organic carbon of the soil after afforestation, which could eventually be restored in a space of time (Paul et al., 2002). According to the surveys carried on in Uruguay, the soil carbon balance is deficient even in 30-year old plantations (Céspedes-Payret, 2007). It would be worse with the present short turn under 10 years. Therefore, under these circumstances, the validity of the sale of 'Carbon Credits' (ecosystem services) as carbon sink should be analysed in forest plantations for industrial purposes.

In the examined cases for Uruguay (soil of medium to low fertility), the carbon balance is negative (Kaemmerer, 1979; Carrasco-Letelier et al., 2004; Céspedes-Payret, 2007) and therefore this trade is scientifically groundless. The same could be argued for similar environmental conditions and crop management in the region.

4.2 Effects of cultivation on the physical and chemical properties of soils

One of the best-known impacts of the afforestation is its effects on the physicochemical properties of the soil (e.g. Burch et al., 1989; Bolin and Sukumar, 2000; Ferreira et al., 2000; Soares and Almeida, 2001; Guo and Gifford, 2002; Jackson et al., 2002; Jobbágy and Jackson, 2003; Whitehead and Beadle, 2004; Jobbágy et al., 2006).

With the afforestation, a series of electrochemical changes occur in the soil resulting in a sudden reduction of pH, an increase of Al^{3+}, a fall of the content of Ca^{2+}, among other variables (e.g. Jobbagy and Jackson, 2003). Authors as Farley et al. (2008) conclude that the grassland afforestation has a consumption of water and cations (mainly, Ca^{2+} and Mg^{2+}) 30% higher than the original grassland, generating the acidification of soil and water runoff.

Impacts are essentially evident in the first few centimetres (A horizon), that portion of the soil where not only the production of agricultural goods is based, but also the production and reproduction of other goods that nature provides to society: the *ecosystem services*.

The whole electrochemical and physicochemical changes that characterise these impacts finally reach their expression at physical level in the structure of the soil, through the gradual increase of its bulk density (Geary, 2001; Céspedes-Payret, 2007) with its impacts in the storage and conduction of water from soils to aquifers.

4.3 Soil and water supply

The runoff from both surface and subsurface and the aquifer recharge depend on the climate and soil characteristics, intrinsic or generated as a result of human activities. Any significant change in vegetation cover leading to alter the properties of soil will necessarily produce a change in the dynamics of water and thus in the hydrological cycle (Ridolfi et al., 2006; Scalon et al., 2006; Jobbágy and Jackson, 2007; Jobbágy et al., 2008; Morgan and Barton, 2008; Nosetto et al., 2008; Santoni et al., 2008; Vanclay, 2009). The well-known impacts of grassland afforestation on the decrease of soil moisture (Heuperman, 1999; Soares and Almeida, 2001; Vertessy et al., 2001; Jobbágy and Jackson, 2004; Engel et al., 2005) are associated not only to land-use change but to multiple factors as the type, age and density of the implanted trees (Lane et al., 2005; Bren and Hopmans, 2007). That is, the impacts resulting from these crops cannot be evaluated by the individual action of each forest enterprise (at plot scale), but by the joint action of all forestry projects within the basin, as well as the spatial distribution of them.

Another determinant of demand for water is how vigorous the plantation is. Available data show that water consumption will be greater as higher the production achieved by the eucalyptus plantation (Vertessy et al., 2003). In Uruguay, these yields are from an average of 10.7 tons (Sorrentino, 1991) to 15 tons of wood per hectare/year (Panario et al., 2006).

In the literature, different ways of measuring the eucalyptus water consumption, made by different authors and for different environments, indicate that the values registered vary in a range of 1.8–5 g of aerial dry wood or dry organic matter per litre of water (Pereira, 1986; Wong and Dunin, 1987; Lima, 1993; Whitehead and Beadle, 2004; Jiménez et al., 2007). In more humid regions, such as Argentinean Pampa, afforestation implanted on grassland soil show evapotranspiration rates of 2–3.7 mm/day (Engel et al., 2005).

In addition, the eucalyptus crops annual water consumption can be very variable according to the different cases, depending on the availability of water in the system. This variation can reach a range between 400 and more than 1500 mm/year (Calvo de Anta, 1992). For this author, the crop estimated demand of water (potential consumption) seem to approach 1200 mm/year. Similar values are registered under pine plantations.

In a survey over 5 years, Shiva and Bandyopadhyay (1987) demonstrated that in terms of lower than average rainfall 1000 mm/year, eucalyptus caused a shortage of soil moisture and groundwater. This deficit was compensated only by one of the years when rainfall reached almost 1500 mm, worth more than the average of Uruguay throughout its territory.

In Uruguay and the region, the issue arises about the possible summer uptake of water from the sub-surface aquifer by eucalyptus, given the broad and extensive development of its root system. Here, the issue becomes more serious when the eucalyptus root system reaches the water table. On the matter Calvo de Anta (1992) and Farley et al. (2005) indicate that examples of this type are relatively frequent in edapho-climatic deficient zones. For Uruguay, Sarli (2004) reported that the NDVI (Normalised Difference Vegetation Index) in eucalyptus plots in drought years shows little change or even increases in relation with grassland, thus indicating that they are using another source of water (superficial layers) for its growth. In the case of the grasslands of the Rio de la Plata basin, a comparative survey performed in two paired watersheds of Uruguay (Lavalleja) and Argentina (Cordoba) shows that their hydrologic yield was reduced by 50% after the implantation of eucalyptus crops (Jobbágy et al., 2006). Moreover, another survey performed in the north of Uruguay, in a river basin of natural grasslands of ~2,000 km^2, especially indicates that the annual hydrologic yield decreased, especially in the summer, after a 25% of its surface was cultivated with eucalyptus (Silveira and Alonso, 2004; Silveira et al., 2006). Salvo et al. (2003) for the period 2001–2003 evaluated the hydric regime of a sandy soil in the NE of Uruguay, concluding that the soil under *E. grandis* always had a significantly lower water content than the soil under grassland, both winter and summer.

On the other hand, Nosetto et al. (2005) made a survey in the Argentinean coast of Uruguay River (Concordia, Entre Ríos) in 117 paired plots covered by eucalyptus or grassland, in order to estimate the value of the evapotranspiration by means of LANDSAT satellite images (for seven dates). The results indicate that from annual rainfall of 1350 mm/year a hydrological yield of 720 mm/year under grassland and 200mm/year under afforestation could be obtained (as predicted by Holmes and Sinclair, 1986; Vertessy et al., 2001, Zhang et al., 2001). This fall, more than 70%, could affect the drinking water supply at the local level and the generation of hydroelectric power at the regional level. Moreover, in years of drought, afforestation could cause a total reduction of some flows. It should be noted that increases in the rates of evapotranspiration under the same rainfall conditions limit available water for other outflows (runoff or groundwater recharge), which are responsible for aquifer recharge and river yields.

Farley et al. (2005) evaluated the changes in the flow delivered in 26 pairs of river basins in pasture regions of four continents, after being afforested. The results include 504 observations of annual flow, and show an average fall of 39% in their hydrologic yield in the afforested river basins. In another work, Jackson et al. (2005) indicate that over more than 600 observations made on 504 annual catchment observations corresponding to 19 countries and five continents plantations decrease stream flow by 227 mm/year globally (52%), with 13% of streams drying completely for at least 1 year.

Another already known phenomenon for decades and observed in Uruguay - which is significant in relation to aquifer recharge - is water repellency (hydrophobicity) in the first few centimetres of soil (Panario et al., 1991; Gutiérrez et al., 1993), and more severe drought conditions during summer in the first centimetres of soil under eucalyptus and pine (Ferreira et al., 2000). This is a phenomenon associated to the great proliferation of a few species of fungi, whose dense web of mycelia (filaments) – of hydrophobic nature – gradually lead to limitations in the soil capacity of humidifying and water infiltration (Bond and Harris, 1964; DeBano and Rice, 1973; Sevink et al., 1989; Scott and Van Wyk, 1990; Panario et al., 1991; Gutiérrez et al., 1993; Ferreira et al., 2000).

With regard to the values of Evapotranspiration (ET), some surveys have registered values of around 1000 mm. They were performed in river basins afforested with eucalyptus in regions with a rainfall greater than 1200 mm/year, while for a rainfall of the order of 500 mm/year, ET is around 450 mm. In the case of pine plantations, the average annual evapotranspiration is not significantly different (Poore and Fries, 1985).

Facing a possible hydric deficit due to plantations, it is possible to expect a worsening of the effects of the droughts as (1) reduced availability of water for other farming productions and industrial activities, (2) shortage of water supplies to towns, (3) difficulties in the generation of hydroelectric energy and (4) modification or destruction of wetlands, as well as of lotic and lentic systems.

4.4 Pesticides in the soil

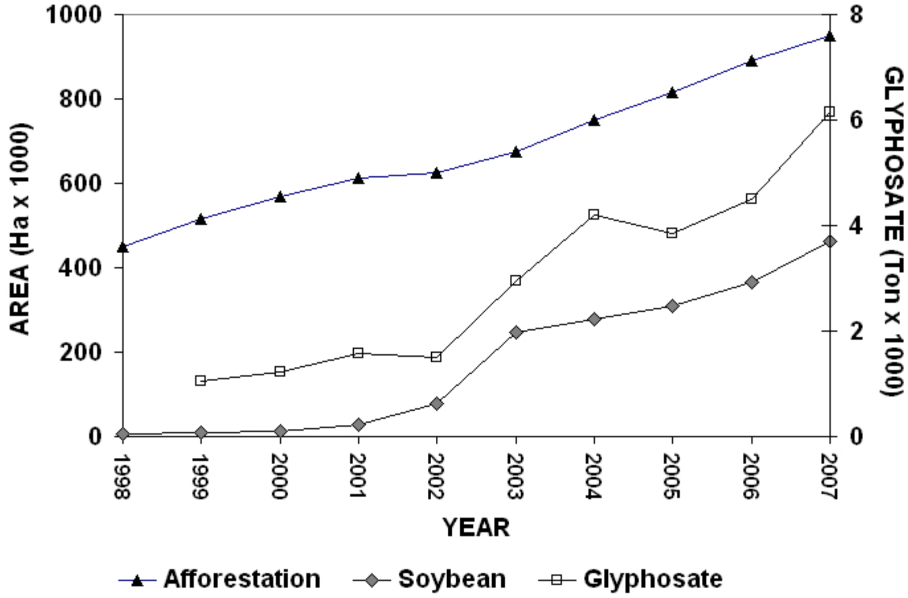
Soil is one of the ecosystem components with greater incidence in the dynamics of agro-chemical residues in the environment (Bohn et al., 1979). Thus, it is able to regulate their transport through sorption/desorption, chelation and complexation processes, or by processes of transformation and degradation through the activity of microorganisms and mesofauna (Martins et al., 2007; Berkowitz et al., 2008; Magga et al., 2008; Pessagno et al., 2008). These properties are a direct function of complexing ligands like citric, oxalic and galic acids, but essentially of more structured complexing acids, like those included in the humic and fulvic soluble fractions (Evans, 1999). Soil organic matter emerges, once more, as a key component to the extent that its degree of availability in the soil conditions the formation of humic-clay complexes. These complexes are critical in determining the amount and distribution of micropores of the soil and consequently, in the dynamics of gases in the respiratory activity and in the amount and distribution of the specific surface of ligands (Sposito, 1989). Both factors exert a direct action on the residues of agrochemicals such as glyphosate (Sundaram and Sundaram, 1997; Borggaard and Gimsing, 2008) whose action, persistence and bioaccumulation in the environment is still the centre of scientific controversy.

4.4.1 The fate of glyphosate

Land-use changes in Uruguay in the last decade and the expansion of glyphosate-tolerant crops and afforestation have been accompanied by the use and import growth of glyphosate [N-(phosphonomethyl)glycine]. Some data in Uruguay are eloquent: in the 1990s, the total area occupied by the soybean and eucalyptus crops was 500,000 hectares, and the import of glyphosate was of 1,000,000 kg of active ingredient. In 2007, that area reached 1,400,000 ha and glyphosate imports grew to 6,000,000 kg of active ingredient (MGAP-DF, 2009; MGAP-DGSSAA, 2009; MGAP-DIEA, 2009) (Figure 3).

In Uruguay, pesticides have been detected in several compartments: blood of exposed and non-exposed populations (Boroukhovitch, 1998), fat and human serum (Rampoldi, 2002; Mañay et al., 2004), soil and water (CARU, 1993; Janiot et al., 1994; Deambrosi, 1996), and food (Dellacassa et al., 1999, Mañay et al., 2004). As in the rest of the world, the glyphosate is the most commonly applied herbicide in Uruguay (near 80%, MGAP-DGSSAA, 2007) and more than 100 clinic cases of human health problems have been reported (Burger and Fernández, 2004).

Figure 3 As the chart shows the growth of the area of forests and soybean crops is associated with increased imports of *glyphosate* in Uruguay (MGAP-DF, 2009; MGAP-DGSSAA, 2009; MGAP-DIEA, 2009) (see online version for colours)



Source: MGAP (2009)

Justifications used to defend the use of this herbicide are, among others: (1) glyphosate is rapidly inactivated in soil and water, (2) it is immobile and does not leach soil (Christoffoleti et al., 2008; Duke and Powles, 2008), (3) it is nearly impossible for glyphosate resistance to evolve in weeds or it may be minimised by simple management measures (Christoffoleti et al., 2008), (4) it has a low irritation potential in eyes and skin and therefore no risk to human health, and (5) it is environmentally safe (Duke and Powles, 2008; Gustafson, 2008).

However, evidence shows that glyphosate (1) is very persistent in soils and sediments (Eberbach, 1998; Fomsgaard et al., 2003; Laitinen et al., 2006), (2) can be easily desorbed from the particles, be highly mobile in the soil and leach to the lower soil (Vereecken, 2005; Borggaard and Gimsing, 2008), (3) can be carried by soil particles suspended in water runoff (Skark et al., 1998), (4) is chemically stable in water and is not tied to photochemical degradation (FAO/OMS, 1986), (5) tops the list of pesticides that cause poisoning in several countries (Royal Society of Chemistry, 1997), including Uruguay (Burger and Fernández, 2004), (6) causes a set of acute symptoms, including recurrent pruritus, respiratory problems, blood pressure increase and allergic reactions (Burger and Fernández, 2004), (7) has led to the emergence of a glyphosate-resistant ryegrass (Bergelson et al., 1998), (8) is toxic to some beneficial arthropods and predators for agriculture (Locke et al., 2008), (9) increases the susceptibility of crops to diseases (Locke et al., 2008) and (10) has harmful effects on the tadpoles of some species of frogs (Relyea, 2005). Moreover, phosphate fertilisers may inhibit the adsorption of glyphosate in soil, keeping it available (Simonsen et al., 2008).

Despite the existence of recent reviews about the glyphosate, the references are still scarce at understanding the role of soil on the dynamics of this herbicide (biodegradation, average time of residence, bioavailability, or transport), its degradation products and surfactants in the soils. Perhaps the controversy regarding the effects of glyphosate-based products could be explained by the level of specialisation of the disciplines, which deal with the subject. Nevertheless, an advanced knowledge of the cause-effect relation of this herbicide in the environment does not imply a deeper understanding of the conditions that determine its mean residence time in cultivated soils and consequently its accumulation and later bioavailability. The contribution provided by those surveys conducted to understand the effects of the land-use change could contribute to surpass those differences from an edaphic point of view. However, the bioavailability of polluting agents as glyphosate is essentially determined by the history of soil use which determines the quantity and quality of organic matter.

4.5 Impacts on biodiversity

The biological diversity can be defined as the property of the different living beings to be varied. Thus, each class of being (gene, cell, individual, community or ecosystem) is expressed in each and all the hierarchic levels of nature, from molecules to ecosystems (Solbrig, 1991). This way, biodiversity does not only depend on species richness, but also on the genetic diversity found within each species, on alpha diversity, i.e. community or habitat diversity in a site, on beta diversity, i.e. temporal or spatial variability of the species within a narrow range of habitat variability, on gamma diversity, i.e. the variability of the landscape within a single ecosystem, and finally it depends on the interactions that occur among these different hierarchical levels in space and time (Halffter and Moreno, 2005).

Biodiversity is used as a parameter to measure the direct or indirect impact of human activities in the ecosystems, particularly, the transformation and simplification of their biotic structure (Halffter and Ezcurra, 1992; Moreno, 2001; Halffter et al., 2005) and from its condition the capacity of resilience of the ecosystem can be inferred. The simplification of the biotic structure is the consequence of the present model of agro-industrial development based on a small number of cultivars. This simplification generates the replacement of a self-organised and resilient system by another much simpler one that is dependent on exogenous income regulated by economic variables. The territorial advance of agriculture over entire habitats produces their irreversible disappearance and, in this way, a generalised process of genetic erosion and loss of resilience. The simpler the cultivar management is (structurally), the greater the impact can be. It is also important to take into consideration the eco-physiological characteristics of the species and variety implanted in relation to those which are replaced. That is, the greater the functional differences of implanted populations with the preexisting ones, greater will be the impact of the land-use change. Also, the larger the size and closeness between productive units are, and greater the intrinsic biodiversity of the habitat affected by the change, greater will be the impact of land-use change.

In the case of Uruguay, this would determine that the implanted afforestation model will maximise these impacts:

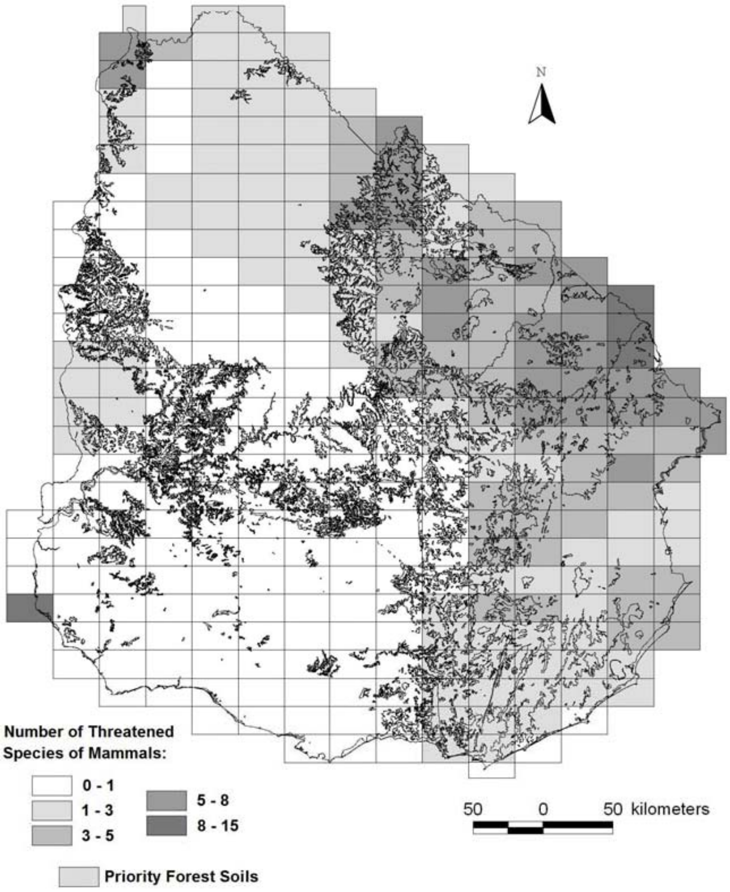
1 Its eco-physiological requirements differ substantially from those of grassland which have co-evolutioned with the other ecosystem components. This is not only because the crop is monospecific, but because of its condition of fast-growing tree.

2 Present management units are usually contiguous and greater than 1,000 ha, sometimes occupying almost all units of soil or site that characterise a habitat.

3 In Uruguay, these productive units also cover biological corridors of importance, as the highlands named 'Sierras del Este', located in the east of the country (in particular in its NE portion) which today have a low level of disturbance, and are characterised by mottled patching of grassland, associated to the presence of small native forest, isolated trees and shrubland.

4 They cover the areas defined as of great diversity of ligneous species (Grela, 2004) naturally associated to a great diversity of fauna, endemic species, as well as, according to Brazeiro et al. (2008) a greater proportion of mammals in danger of extinction (Figure 4).

Figure 4 Geographical distribution of the number of threatened species of mammals in Uruguay (Brazeiro et al., 2008) and the distribution of 'priority forest soils'



5 Summary

The transfer of tree plantations and pulp mill industry towards the Rio de la Plata basin is basically due to a series of advantages in the current worldwide context. Among other advantages, lower production cost of raw materials, access and use of water for free, cheap land, fertile soils, legal gaps, lower requirements on environmental control, tax exemptions are considered.

The intensity in the use and management of the natural resources affected to these large-scale production systems brings along a series of still unknown environmental disruptions. These disruptions include not only those specific to the cellulose pulp extraction process, but also those involved in tree plantations, i.e. the production phase of raw materials. In this phase, these disruptions are not so evident and easy to measure.

Nevertheless, there is a considerable amount of scientific background to say that the grassland afforestation leads to an alteration of the physicochemical properties of the original soil, a decline in the yield of water in the catchment's area and water table, causing a severe negative impact on biodiversity.

An increase in the *environmental liability* is the economic result of the impact on all soil and water parameters affected by the conversion of grassland to tree plantations.

The loss of ecosystem services provided by the grassland becomes an increase in direct and indirect spending by the State. In fact, in a shorter or longer term, the State will have to bear the costs of externalities (e.g. erosion and flood control, pronounced droughts hydric deficit mitigation, replacement of soil nutrients with synthetic fertilisers, pest control through synthetic compounds, etc.).

As noted, the global value of services without a market price may exceed the GDP of a country.

From a social point of view, the summarised aspects result in a reduction in the margins of freedom in terms of food safety. Food production in the next years, and the access in amount and quality to them, constitutes one of the major challenges. The accesses to other minor goods of social consumption as the cellulose pulp is not so.

Future research should further study these and other environmental impacts and also about the limits of resilience of the affected systems. But above all, enough information is not available yet, and requires further complex interdisciplinary approaches.

Acknowledgements

We sincerely thank Agricultural Engineer Anahit Aharonian for editing the English version of this work and especially for her dedication and enthusiasm. Funding for this work was provided by the Inter-American Institute for Global Change Research (IAI) (CRN II 2031), which is supported by the US National Science Foundation (Grant GEO-0452325).

References

Alexander, S., Schneider, S. and Lagerquist, K. (1997) 'Ecosystem services: interaction of climate and life', in Daily, G. (Ed.): *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press, Washington, D.C., pp.71–92.

Altesor, A., Di Landro, E., May, H. and Ezcurra, E. (1998) 'Long-term species change in a Uruguayan grassland', *Journal of Vegetation Science*, Vol. 9, pp.173–180.

Altesor, A., Eguren, G., Mazzeo, N., Panario, D. and Rodríguez, C. (2008) 'La industria de la celulosa y sus efectos: certezas e incertidumbres', *Ecología Austral*, Vol. 18, pp.291–303.

Alvarez, R. and Alvarez, C.R. (2000) 'Soil organic matter pools and their association with carbon mineralization kinetics', *Soil Science Society of America Journal*, Vol. 64, pp.184–189.

Bale, J.S., van Lenteren, J.C. and Bigler, F. (2008) 'Biological control and sustainable food production', *Philosophical Transactions of the Royal Society B*, No. 363, pp.761–776.

Bergelson, J., Purrington, C.B. and Wichmann, G. (1998) 'Promiscuity in transgenic plants', *Nature*, Vol. 395, pp.25–26.

Berkowitz, B., Dror, I. and Yaron, B. (2008) *Contaminant Geochemistry, Interactions and Transport in the Subsurface*, Springer, Heidelberg, Berlin.

Bishop, J. and Landell-Mills, N. (2002) 'Forest environmental services: an overview', in Pagiola, S., Bishop, J. and Landel-Mills, N. (Eds): *Selling Forest Environmental Services. Market-based Mechanisms for Conservation and Development*, Earthscan Publications Ltd., UK, pp.15–36.

Bohn, H., McNeal, B. and O'Connor, G. (1979) *Soil Chemistry*, Wiley, New York.

Bolin, B. and Sukumar, R. (2000) 'Global perspective', in Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.J. and Dokken, D.J. (Eds): *Land, Use, Land Use Change, and Forestry*, A special report of the Intergovernmental Panel on Climate Change, Cambridge University Press, UK, pp.25–51.

Bond, R.D. and Harris, J.R. (1964) 'The influence of the microflora on the physical properties of soils. I. Effects associated with filamentous algae and fungi', *Australian Journal of Soil Research*, Vol. 2, pp.111–122.

Borggaard, O.K. and Gimsing, A.L. (2008) 'Fate of glyphosate in soil and the possibility of leaching to ground and surface waters: a review', *Pest Management Science*, Vol. 64, pp.441–456.

Boroukhovitch, M. (1998) 'Current state of chlorine containing pesticides in Uruguay', *Proceedings of the Subregional Awareness Raising Workshop on Persistent Organic Pollutants (POPs)*, 1–3 April, Puerto Iguazú, Argentina. Available online at: http://www.chem.unep.ch/pops/POPs_Inc/proceedings/Iguazu/URUGUAYE.html (accessed on 13 January 2009).

Brazeiro, A., Achkar, M., Canavero, A., Fagúndez, C., González, E., Grela, I., Lezama, F., Maneyro, R., Barthesagy, L., Camargo, A., Carreira, S., Costa, B., Nuñez, D., da Rosa, I. and Toranza, C. (2008) *Prioridades geográficas para la conservación de la biodiversidad terrestre de Uruguay*, Resumen ejecutivo, Uruguay, Proyecto PDT No. 3226.

Bren, L. and Hopmans, P. (2007) 'Paired catchments observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia', *Journal of Hydrology*, Vol. 336, pp.416–429.

Burch, G.J., Moore, I.D. and Burns, J. (1989) 'Soil hydrophobic effects on infiltration and catchment runoff', *Hydrological Processes*, Vol. 3, pp.211–222.

Burger, M. and Fernández, S. (2004) 'Exposición al herbicida glifosato: aspectos clínicos toxicológicos', *Revista Médica del Uruguay*, Vol. 20, No. 3, pp.202–207.

Cabrera, A.L. (1971) 'Fitogeografía de la República Argentina', *Boletín de la Sociedad Argentina de Botánica*, Vol. 14, Nos. 1–2, pp.1–42.

Cabrera, A.L. (1976) 'Regiones fitogeográficas argentinas', in Kugler, W.F. (Ed.): *Enciclopedia Argentina de Agricultura y Jardinería II*, ACME, Buenos Aires, pp.1–85.

Cabrera, A.L. and Willink, A. (1973) *Biogeografía de América Latina*, Washington D.C.: Secretaría General de la Organización de los Estados Americanos. Programa Regional de Desarrollo Científico y Tecnológico, Departamento de Asuntos Científicos. (Monografía No. 13. Serie de Biología).

Calvo de Anta, R. (1992) *El eucalipto en Galicia: sus relaciones con el medio natural*, Santiago de Compostela: Servicio de Publicaciones e Intercambio, Universidad de Santiago de Compostela.

Carrasco-Letelier, L., Eguren, G., Castiñeira, C., Parra, O. and Panario, D. (2004) 'Preliminary study of prairies forested with *Eucalyptus* sp. at the Northwestern Uruguayan soils', *Environmental Pollution*, Vol. 127, pp.49–55.

CARU (1993) *II Seminario de Calidad de Aguas y control de la Contaminación del Río Uruguay. Colón, Argentina*. Comisión Administradora del Río Uruguay (CARU). Available online at: www.caru.org.uy/publicaciones/2doSeminario-de-calidad-de-aguas-y-control-de-la-contaminacion-en-el-Rio-Uruguay.pdf (accessed on 9 January 2009).

Céspedes-Payret, C. (2007) *Dinámica de la materia orgánica en relación con algunos parámetros fisicoquímicos en la conversión de pradera a cultivo forestal un Mollisol en la zona de Piedras Coloradas-Algorta, Uruguay*, PhD Thesis, Ecole Supérieure d´Agronomie de Toulouse, Institut National Polytechnique, Francia.

Christoffoleti, P.J., Galli, A.J.B., Carvalho, S.J.P., Moreira, M.S., Nicolai, M., Foloni, L.L., Martins, B.A.B. and Ribeiro, D.N. (2008) 'Glyphosate sustainability in South American cropping systems', *Pest Management Science*, Vol. 64, pp.422–427.

CONEAT (1979) *Grupos de Suelos. Indices de Productividad*, Montevideo: Comisión Nacional de Estudio Agroeconómico de la Tierra, Ministerio de Agricultura y Pesca.

Costanza, R.R., D´Arge, R., De Groot, S., Farber, M., Grasso, B., Hannon, K., Limburg, S., Naeem, R.V., O´Neill, J., Paruelo, R., Raskin, G., Sutton, P. and Van den Belt, M. (1997) 'The value of the world's ecosystem services and natural capital', *Nature*, Vol. 357, pp.253–260.

Daily, G.C., Matson, P.A. and Vitousek, P.M. (1997) 'Ecosystem services supplied by soil', in Daily, G. (Ed.): *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press, Washington, D.C., pp.113–132.

De Groot, R., Wilson, M. and Boumans, R. (2002) 'A typology for the classification, descriptions and valuation of ecosystem functions, goods and services', *Ecological Economics*, Vol. 41, pp.393–408.

Deambrosi, E. (1996) 'Plaguicidas utilizados en el cultivo de arroz', *Revista Arroz*, Vol. 7, No. 2, pp.29–33.

DeBano, L.F. and Rice, R.M. (1973) 'Water repellent soils: their implications in forestry', *Journal of Forestry*, Vol. 7, No. 1, pp.220–223.

Dellacassa, E., Lorenzo, D., Di Bella, G. and Dugo, G. (1999) 'Pesticide residues in Uruguayan lemon oils', *Journal of Essential Oil Research*, Vol. 11, pp.465–469.

Duarte, C. (Ed.), Alonso, S., Benito, G., Dachs, J., Montes, C., Pardo, M., Rios, A., Simó, R. and Valladares, F. (2006) *Cambio Global: Impacto de la actividad humana sobre el sistema Tierra*, Consejo Superior de Investigaciones Científicas, Madrid.

Duke, S.O. and Powles, S.B. (2008) 'Glyphosate: a once-in-a-century herbicide', *Pest Management Science*, Vol. 64, pp.319–325.

Eberbach, P. (1998) 'Applying non-steady-state compartmental analysis to investigate the simultaneous degradation of soluble and sorbed Glyphosate (N-(Phosphonomethyl)glycine) in four soils', *Pesticide Science*, Vol. 52, pp.229–240.

Engel, V., Jobbágy, E.G., Stieglitz, M., Williams, M. and Jackson R.B. (2005) 'Hydrological consequences of Eucalyptus afforestation in the Argentine Pampas', *Water Resources Research*, Vol. 41, W10409.

Eva, H.D., Belward, A.S., de Miranda, E.E., DiBella, C.M., Gond, V., Huber, O., Jones, S., Sgrenzaroli, M. and Fritz, S. (2004) 'A land cover map of South America', *Global Change Biology*, Vol. 10, pp.731–744.

Evans, D.J.A. (1989) 'Chemistry of metal retention by soils', *Environmental Science and Technology*, Vol. 23, No. 9, pp.1046–1056.

FAO/OMS (1986) *Pesticide Residues in Food – 1986; Reunión Conjunta FAO/OMS sobre Residuos de Plaguicidas (JMPR)*, Plant Production and Protection Paper 77, Rome: FAO.

Farley, K.A., Jobbágy, E.G. and Jackson, R.B. (2005) 'Effects of afforestation on water yield: a global synthesis with implications for policy', *Global Change Biology*, Vol. 11, pp.1565–1576.

Farley, K.A., Piñeiro, G., Palmer, S.M., Jobbágy, E.G. and Jackson, R.B. (2008) 'Stream acidification and base cation losses with grassland afforestation', *Water Resources Research*, Vol. 44, W00A03.

Ferreira, A.J.D., Coelho, C.O.A., Walsh, R.P.D., Shakesby, R.A., Ceballos, A. and Doerr, S.H. (2000) 'Hydrological implications of soil water-repellency in *Eucalyptus globules* forests, north-central Portugal', *Journal of Hydrology*, Vol. 231, pp.165–177.

Fomsgaard, I.S., Spliid, N.H. and Felding, G. (2003) 'Leaching of pesticides through normal-tillage and low-tillage soil – a lysimeter study. II. Glyphosate', *Journal of Environmental Science and Health Part B*, Vol. 38, No. 1, pp.19–35.

Freeman, M.C., Pringle, C.M. and Jackson, C.R (2007) 'Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales', *Journal of the American Water Resources Association*, Vol. 43, No. 1, pp.5–14.

Geary, T.F. (2001) 'Afforestation in Uruguay: study of a changed landscape', *Journal of Forestry*, Vol. 99, No. 7, pp.35–39.

Grela, I. (2004) *Geografía florística de las especies arbóreas de Uruguay: propuesta para la delimitación de dendrofloras*, MSc Thesis, Maestría en Ciencias Biológicas, Opción Botánica, PEDECIBA, Universidad de la República, Montevideo, Uruguay.

Guo, L.B. and Gifford, R.M. (2002) 'Soil carbon stocks and land-use change: a meta analysis', *Global Change Biology*, Vol. 8, pp.345–360.

Gustafson, D. (2008) 'Sustainable use of glyphosate in North American cropping systems', *Pest Management Science*, Vol. 64, pp.409–416.

Gutiérrez, O. (Ed.), Caffera, R., Céspedes, C., González, A., Gutiérrez, O. and Panario, D. (1993) 'Hacia una evaluación de efectos ambientales de la forestación en Uruguay con especies introducidas', in Pérez Arrarte, C. (Ed.): *Desarrollo forestal y medioambiente*, CIEDUR/Hemisferio Sur, Montevideo, pp.157–206.

Halffter, G. and Ezcurra, E. (1992) '¿Qué es la biodiversidad?', in Halffter, G. (Ed.): *La diversidad biológica en Iberoamérica I*, Xalapa, Veracruz, México, pp.2–24.

Halffter, G. and Moreno, C.E. (2005) 'Significado biológico de las diversidades Alfa, Beta y Gamma', in Halffter, G., Soberón, J., Koleff, P. and Melic, A. (Eds): *Sobre Diversidad Biológica: El significado de las Diversidades Alfa, Beta y Gamma*, Vol. 4, Sociedad Entomológica Aragonesa, Zaragoza, España, Monografías del Tercer Milenio, pp.5–18.

Halffter, G., Soberón, J., Koleff, P. and Melic, A. (Eds) (2005) *Sobre Diversidad Biológica: El significado de las Diversidades Alfa, Beta y Gamma*, Vol. 4, Sociedad Entomológica Aragonesa, Zaragoza, España, Monografías del Tercer Milenio.

Henderson, G.S. (1995) 'Soil organic mater: a link between forest management and productivity', in McFee, W.W. and Kelly, J.M. (Eds): *Carbon Forms and Functions in Forest Soils*, Soil Science Society of America, SSSA, Inc., Madison, WI, pp.419–435.

Heuperman, A (1999) 'Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems', *Agricultural Water Management*, Vol. 39, pp.153–167.

Holmes, J.W. and Sinclair, J.A. (1986) 'Water yield from some afforested catchments in Victoria', *Proceedings of the Hydrology and Water Resources Symposium*, 25–27 November, The Institution of Engineers, Griffith University, Brisbane, Australia, pp.214–218.

Houghton, R.A. (2001) 'Global terrestrial productivity and carbon balance', in Roy, J., Saugier, B. and Mooney, H.A. (Eds): *Terrestrial Global Productivity*, Academic Press, San Diego, pp.499–520.

Jackson, R.B., Banner, J.L., Jobbágy, E.G., Pockmann, W.T. and Wall, D.H. (2002) 'Ecosystem carbon loss with woody plant invasion of grassland', *Nature*, Vol. 418, pp. 623–626.

Jackson, R.B, Jobbágy, E.G., Avissar, R, Baidya Roy, S., Barrett, D.J., Cook, Ch. W., Farley, K.A., le Maitre, D.C., McCarl, B.A. and Murray, B.C. (2005) 'Trading water for carbon with biological carbon sequestration', *Science*, Vol. 310, pp.1944–1947.

Janiot, L.J., Sericano, J.L. and Roses, O.E. (1994) 'Chlorinated pesticide occurrence in the Uruguay River (Argentina-Uruguay)', *Water, Air and Soil Pollution*. Vol. 76, pp.323–331.

Jiménez, E., Vega, J.A., Pérez-Gorostiaga, P., Fonturbel, T., Cuiñas, P. and Fernández, C. (2007) 'Evaluación de la transpiración de *Eucalyptus globulus* mediante la densidad de flujo de savia y su relación con variables meteorológicas y dendométricas', *Boletín del Centro de Investigación y Documentación del Eucalipto*, Vol. 3, pp.119–138.

Jobbágy, E.G. and Jackson, R.B. (2003) 'Patterns and mechanisms of soil acidification in the conversion of grasslands to forest', *Biogeochemistry*, Vol. 64, pp.205–229.

Jobbágy, E.G. and Jackson, R.B. (2004) 'Groundwater use and salinization with grassland afforestation', *Global Change Biology*, Vol. 10, pp.1299–1312.

Jobbágy, E.G. and Jackson, R.B. (2007) 'Groundwater and soil chemical changes under phreatophytic tree plantations', *Journal of Geophysical Research*, Vol. 112, G02013.

Jobbágy, E.G., Vasallo, M., Farley, K.A, Piñeiro, G., Garbulsky, M.F., Nosetto, M.D, Jackson, R.B. and Paruelo J.M. (2006) 'Forestación en pastizales: Hacia una visión integral de sus oportunidades y costos ecológicos', *Agrociencia*, Vol. 10, pp.109–124.

Jobbágy, E.G., Nosetto, M., Santoni, C. and Baldi, G. (2008) 'El desafío ecohidrológico de las transiciones entre sistemas leñosos y herbáceos en la llanura Chaco-Pampeana', *Ecología Austral*, Vol. 18, pp. 305–322.

Kaemmerer, M. (1979) *Contribution à l'étude de l'évolution de la matière organique dans quelques sols d'Uruguay sous différents systèmes agro-écologiques*, PhD Thesis, ENSAIA (INP de Lorraine), Nancy, Francia.

Kumar, V., Bellinder, R.R., Brainard, D.C., Malik, R.K. and Gupta, R.K (2008) 'Risks of herbicide-resistant rice in India: A review', *Crop Protection*, Vol. 27, Nos. 3–5, pp.320–329.

Laitinen, P., Siimes, K., Eronen, L., Ramo, S., Welling, L., Oinonen, S., Mattsoff, L. and Ruohonen-Lehto, M. (2006) 'Fate of the herbicides glyphosate, glufosinate-ammonium, phenmedipham, ethofumesate and metamitron in two Finnish arable soils', *Pest Management Science*, Vol. 62, pp.473–491.

Lal, R. (2005) 'Soil erosion and carbon dynamics', *Soil and Tillage Research*, Vol. 81, pp.137–142.

Lane, P.N.J., Best, A.E., Hickel, K. and Zhang, L. (2005) 'The response of flow duration curves to afforestation', *Journal of Hydrology*, Vol. 310, pp.253–265.

Lima, W. de P. (1993) *Impacto Ambiental do Eucalipto*, 2a. ed., EDUSP (Editorial da Universidad de Sao Paulo), Sao Paulo.

Locke, M.A., Zablotowicz, R.M. and Reddy, K.N. (2008) 'Integrating soil conservation practices and glyphosate-resistant crops: impacts on soil', *Pest Management Science*, Vol. 64, pp.457–469.

Magga, Z., Tzovolou, D.N., Theodoropoulou, M.A., Dalkarani, T., Pikios, K. and Tsakiroglou, Ch. D. (2008) 'Soil column experiments used as a means to asess transport, sorption, and biodegradation of pesticides in groundwater', *Journal of Environmental Science and Health Part B.*, Vol. 43, pp.732–741.

Mañay, N., Rampoldi, O., Alvarez, C., Piastra, C., Heller, T., Viapiana, P. and Korbut, S. (2004) 'Pesticides in Uruguay', *Review of Environmental Contamination and Toxicology*, Vol. 181, pp.111–138.

Maquere, V., Laclau, J.P., Bernoux, M., Saint-Andre, L., Goncalves, J.L.M., Cerri, C.C., Piccolo, M.C. and Ranger, J. (2008) 'Influence of land use (savanna, pasture, *Eucalyptus* plantations) on soil carbon and nitgrogen stocks in Brazil', *European Journal of Soil Science*, Vol. 59, pp.863–877.

Martins, E.L., Weber, O.L.S., Dores, E. and Spadotto, C.A. (2007) 'Leaching of seven pesticides currently used in cotton crop in Mato Grosso State-Brazil', *Journal of Environmental Science and Health Part B*, Vol. 42, pp.877–882.

McAfee, K. (2008) 'Beyond techno-science: transgenic maize in the fight over Mexico's future', *Geoforum*, Vol. 39, pp.148–160.

McBride, M.B. (1994) *Environmental Chemistry of Soils*, Oxford, New York, Oxford University Press, United Kingdom.

MGAP-DF (2009) Ministerio de Ganadería, Agricultura y Pesca. Dirección Forestal. Available online at: http://www.mgap.gub.uy/Forestal/DGF.htm (accessed on 14 January 2009).

MGAP-DGSSAA (2007) Ministerio de Ganadería, Agricultura y Pesca. Dirección General de Servicios Agrícolas. Available online at: www.mgap.gub.uy/dgssaa/DivAnalisisDiagnostico/documentosDAYD/Resumen%20Set%2008.xls (accessed on 9 January 2009).

MGAP-DGSSAA (2009) Ministerio de Ganadería, Agricultura y Pesca. Dirección General de Servicios Agrícolas. Available online at: http://www.mgap.gub.uy/DGSSAA/DivAnalisisDiagnostico/DAYD_PROFIT_ESTADISTICA.htm (accessed on 14 January 2009).

MGAP-DIEA (2009) Ministerio de Ganadería, Agricultura y Pesca – Dirección de Estadísticas Agropecuarias. 'Sistema de Información Censo Agropecuario 2000' – SICA. Available online at: http://www.mgap.gub.uy/Ddiea/CENSO2000\censo_general_agropecuario_2000.htm (accessed on 14 January 2009).

Moreno, C.E. (2001) *Métodos para medir la biodiversidad*, Manuales y Tesis SEA (Sociedad Entomológica Aragonesa), Vol. 1, Zaragoza, España. Available online at: http://www.sea-entomologia.org/Publicaciones/ManualesTesis/ManualesTesis1/ManualesTesis1.htm (accessed on 29 January 2009).

Morgan, H.D. and Barton, C.V.M. (2008) 'Forest-scale sap flux responses to rainfall in a dryland eucalyptus plantation', *Plant Soil*, Vol. 305, pp.131–144.

Morrone, J.J. (2001) *Biogeografia de América Latina y el Caribe*. Manuales y Tesis S.E.A. (Sociedad Entomológica Aragonesa), Vol. 3, Zaragoza. Available online at: http://www.sea-entomologia.org/Publicaciones/ManualesTesis/ManualesTesis3/manualestesis3.htm (accessed on 29 January 2009).

Morrone, J.J. (2006) 'Biogeographic areas and transition zones of Latin America and the Caribbean Islands based on panbiogeographic and cladistic analyses of the entomofauna', *Annual Review of Entomology*, Vol. 51, pp.467–494.

Nosetto, M.D., Jobbágy, E.G. and Paruelo, J.M. (2005) 'Land use change and water losses: the case of grassland afforestation across a soil textural gradient in Central Argentina', *Global Change Biology*, Vol. 11, pp.1101–1117.

Nosetto, M.D., Jobbágy, E.G., Tóth, T. and Jackson, R.B. (2008) 'Regional patterns and controls of ecosystem salinization with grassland afforestation along a rainfall gradient', *Global Biogeochemical Cycles*, Vol. 22, GB2015.

Panario, D. (2001) 'Una Perspectiva ambiental de la utilización de vegetales genéticamente modificados en agricultura', in Marín, M., Battistoni, J., Sanguinetti, C. and Señorale, M. (Eds): *Organismos Genéticamente Modificados, Reflexiones del Sur*, Ed.Trilce, Montevideo, pp.125–131.

Panario, D. and Bidegain, M. (1997) 'Climate change effects on grasslands in Uruguay', *Climate Research*, Vol. 9, pp.37–40.

Panario, D. and Gutiérrez, O. (2007) 'La política forestal industrial del estado Uruguayo'. *Paper Presented at Seminario: Política y Pasteras en el Rio Uruguay: Medio Ambiente, Modelos Productivos y Movimiento Social*, UNSAM (Universidad Nacional de San Martín), 16 November, Buenos Aires, Argentina. Available online at: http://www.unsam.edu.ar/escuelas/humanidades/pastera.htm (accessed on 19 January 2009).

Panario, D. (Ed.), Caffera, R., Céspedes, C., González, A., Gutiérrez, O. and Panario, D. (1991) *Desarrollo forestal y medio ambiente en Uruguay - 11 - Hacia una evaluación de efectos ambientales de la forestación en Uruguay con especies introducidas*, CIEDUR, Montevideo, Serie Investigaciones No. 85.

Panario, D., Mazzeo, N. Eguren, G., Rodríguez, C. Altesor, A. Cayssials, R. and Achkar, M. (2006) *Síntesis de los efectos ambientales de las plantas de celulosa y del modelo forestal en Uruguay*, Montevideo, Informe Facultad de Ciencias. Universidad de la República. Available online at: www.fcien.edu.uy/archivo/informe_consejo_plantas_celulosa_28_06_06 (accessed on 24 January 2009).

Paruelo, J.M., Garbulsky, M.F., Guerschman, J.P. and Jobbágy, E.G. (2004) 'Two decades of NDVI in South America: identifying the imprint of global changes', *International Journal of Remote Sensing*, Vol. 25, pp.2793–2806.

Paruelo, J.M., Guerschman, J.P., Piñeiro, G., Jobbágy, E.G., Verón, S.R., Baldi, G. and Baeza, S. (2006) 'Cambios en el uso de la tierra en Argentina. Marcos conceptuales para su análisis', *Agrociencia*, Vol. X, pp.47–61.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G. and Khanna, P.K. (2002) 'Change in soil carbon following afforestation', *Forest Ecology and Management*, Vol. 168, pp.241–257.

Paustian, K., Six, J., Elliott, E.T. and Hunt, H.W. (2000) 'Management options for reducing CO_2 emissions from agricultural soils', *Biogeochemistry*, Vol. 48, pp.147–163.

Pereira, J.S. (1986) 'O consume de agua pela floresta, ecofisiologia das relacoes planta-agua no caso do eucalipto em Portugal', *Paper Presented at the Seminario: O Eucalipto, a Água e o Solo*, Sociedade Portuguesa de Ciências Florestais, 1–2 April, Lisboa, Portugal.

Pessagno, R.C., Torres Sánchez, R.M. and dos Santos Afonso, M. (2008) 'Glyphosate behavior at soil and mineral-water interfaces', *Environmental Pollution*, Vol. 153, pp.53–59.

Poore, M.E.D. and Fries, C. (1985) *Efectos ecológicos de los eucaliptos*, Food and Agriculture Organization, Roma, Italia, FAO Technical Study No. 59.

Povirk, K.L., Welker, J.M. and Vance, G.F. (2001) 'Carbon sequestration in Arctic and Alpine tundra and mountain meadow ecosystem', in Follet, R.F., Kimble, J.M. and Lal, R. (Eds): *The potential of US Grazing Lands to Sequester Carbon and Mitigate Greenhouse Effect*, Lewis Publishers, Boca Raton, FL, pp.189–228.

Rampoldi, O. (2002) 'Residuos biológicos en alimentos de origen animal. Experiencia del Programa Nacional', *Paper Presented at the II Congreso Uruguayo de Toxicología Clínica*, 14–17 May, Montevideo, Uruguay.

Redes (2008) Difunden en Buenos Aires 'Impactos de la Forestación en Uruguay'. Obtained through the Internet: http://www.redes.org.uy/2008/02/22/difunden-en-buenos-aires-impactos-de-la-forestacion-en-uruguay (accessed on 7 January 2009).

Reichenberger, S., Bach, M, Skitschak, A. and Frede, H.G. (2007) 'Mitigation strategies to reduce pesticide inputs into ground – and surface water and their effectiveness – a state of the art, review', *Science of the Total Environment*, Vol. 384, pp.1–35.

Relyea, R.A. (2005) 'The lethal impact of Roundup on aquatic and terrestrial amphibians', *Ecological Applications*, Vol. 15, pp.1118–1124.

Ridolfi, L., D'Odorico, P. and Laio, F. (2006) 'Effect of vegetation-water table feedbacks on the stability and resilience of plant ecosystems', *Water Resources Research*, 42, W01201.

Royal Society of Chemistry (1997) *Pesticide Outlook*, Vol. 8, No. 6, pp.3–4.

Salvo, L., Delgado, S., Préchac, F.G., Hernández, J., Amarante, P and Hill, M. (2003) 'Régimen hídrico de un Ultisol arenoso del noreste de Uruguay bajo plantaciones de *Eucalyptus grandis* vs. Pasturas', in Luján, D.L., Gabriels, D and Soto, G. (Eds): *Evaluación de Parámetros y Procesos Hidrológicos en el Suelo*, VII Escuela Latinoamericana de Física de Suelos, La Serena, Chile, pp.65–69.

Santoni, C.S., Jobbágy, E.G., Marchesini, V. and Contreras, S. (2008) 'Diferentes usos del suelo: consecuencias sobre balance hídrico y drenaje profundo en zonas semiáridas', *Paper presented at XXI Congreso Argentino de la Ciencia del Suelo*, 13–16 May, San Luis, Argentina.

Sarli, V. (2004) *Impacto del cambio en el uso del suelo sobre el funcionamiento ecosistémico. Departamentos de Paysandú y Río Negro, Uruguay*, MSc Thesis, Maestría en Ciencias Ambientales, Facultad de Ciencias, UDELAR, Montevideo, Uruguay.

Scalon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gayer, C.B., Edmunds, W.M. and Simmers, I. (2006) 'Global synthesis of groundwater recharge in semiarid and arid regions', *Hydrological Processes*, Vol. 20, pp.3335–3370.

Scott, D.F. and Van Wyk, D.B. (1990) 'The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment', *Journal of Hydrology*, Vol. 121, pp.239–256.

Sevink, J., Imeson, A.C. and Verstrate, J.M. (1989) 'Humus form development and hillslope runoff, and the effects of fire and management under Mediterranean forest in NE Spain', *Catena*, Vol.16, pp.461–475.

Seybold, C.A., Mausbach, J.J., Karlen, D.L. and Rogers, H.H. (1997) 'Quantification of soil quality', in Lal, R., Kimble, J.M, Follet, R.F. and Stewart, B.A. (Eds): *Soil Process and the Carbon Cycle*, CRC Press, Boca Raton, FL, pp.387–404.

Shiva, V. and Bandyopadhyay, J. (1987) *Ecological Audit of Eucalyptus cultivation*, Research Foundation for Science & Ecology Dehra Dun, New Delhi.

Sikora, L.J. and Stott, D.E. (1996) 'Soil organic carbon and nitrogen', in Doran, J.W. and Jones, A.J. (Eds): *Methods for Assessing Soil Quality*, Soil Science Society of America, Madison, WI, pp.157–167.

Silveira, L. and Alonso, J. (2004) 'Modificación de los coeficientes de escorrentía producto del desarrollo forestal en una macrocuenca del Uruguay', *Paper Presented at the XXI Congreso Latinoamericano de Hidráulica, Asociación Internacional de Investigaciones e Ingeniería Hidráulica (AIIH)*, 18–22 October, San Pablo, Brasil.

Silveira, L., Alonso, J. and Martínez, L. (2006) 'Efecto de las plantaciones forestales sobre el recurso agua en el Uruguay', *Agrociencia*, Vol. X, pp.75–93.

Simonsen, L., Fomsgaard, I.S., Svensmark, B. and Spliid, N.H. (2008) 'Fate and availability of glyphosate and AMPA in agricultural soil', *Journal of Environmental Science and Health Part B*, Vol. 43, pp.35–375.

Six, J. and Jastrow, J.D. (2002) 'Organic Matter Turnover', in Lal, R. (Ed.): *Encyclopedia of Soil Science*, Marcel Dekker, New York, pp.936–942.

Skark, Ch., Zullei-Seibert, N., Schottler, U. and Schlett, C. (1998) 'The occurrence of glyphosate in surface water', *International Journal of Environmental Analytical Chemistry*, Vol. 70, pp.93–104.

Soares, J.V. and Almeida, A.C. (2001) 'Modelling the water balance and soil water fluxes in a fast growing eucalyptus plantation in Brazil', *Journal of Hydrology*, Vol. 253, pp.130–147.

Solbrig, O.T. (Ed.) (1991) *From Genes to Ecosystems: a Research Agenda for Biodiversity*, Report of a IUBS-SCOPE-UNESCO, Harvard Forest.

Sorrentino, A. (1991) *Índices de sitios preliminares para las principales especies forestales cultivadas en Uruguay*, Facultad de Agronomía, Universidad de la República, Montevideo, Boletín Investigación No. 33.

Sposito, G. (1989) *The Chemistry of Soils*, Oxford University Press, New York.

Sundaram, A. and Sundaram, K.M.S. (1997) 'Solubility products of six metal-glyphosate complexes in water and forestry soils, and their influence on glyphosate toxicity to plants', *Journal of Environmental Science and Health Part B*, Vol. 32, No. 4, pp.583–598.

van Dijk, A.I.J.M. and Keenan, R.J. (2007) 'Planted forests and water in perspectiva', *Forest Ecology and Management*, Vol. 251, Nos. 1–2, pp.1–9.

Vanclay, J.K. (2009) 'Managing water use from forest plantations', *Forest Ecology and Management*, Vol. 257, pp.385–389.

Vereecken, H (2005) 'Mobility and leaching of glyphosate: a review', *Pest Management Science*, Vol. 61, pp.1139–1151.

Vertessy, R.A., Watson, F.G.R. and O'Sullivan, S.K. (2001) 'Factors determining relations between stand age and catchment water balance in mountain ash forests', *Forest Ecology and Management*, Vol. 143, pp.13–26.

Vertessy, R.A., Zhang, L. and Dawes, W.R. (2003) 'Plantations, river flows and river salinity', *Australian Forestry*, Vol. 66, pp.55–61.

Whitehead, D. and Beadle, Ch. L. (2004) 'Physiological regulation of productivity and water use in Eucalyptus: a review', *Forest Ecology and Management*, Vol. 193, pp.113–140.

Wolfenbarger, L.L and Phifer, P.R. (2000) 'The ecological risks and benefits of genetically engineered plants', *Science*, Vol. 290, No. 5499, pp.2088–2093.

Wong, S.C. and Dunin, F.X. (1987) 'Photosynthesis and transpiration of trees in a eucalypt forest stand: CO_2, light and humidity responses', *Australian Journal of Plant Physiology*, Vol. 14, No. 6, pp.619–632.

Zhang, L., Dawes, W.R. and Walker, G.R. (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale', *Water Resources Research*, Vol. 37, No. 3, pp.701–708.

Note

1 CONEAT groups are not strictly soil basic cartographic units, but they constitute homogeneous areas in terms of productive capacity of cattle meat and wool.