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Bromus tectorum invasion in South America: Patagonia under threat?

K L SPEZIALE*, S A LAMBERTUCCI* & C EZCURRA*†

*Laboratorio Ecotono, INIBIOMA-CONICET, Universidad Nacional del Comahue, Bariloche, Argentina, and †Departamento de Botánica, INIBIOMA-CONICET, Universidad Nacional del Comahue, Bariloche, Argentina

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Summary

Bromus tectorum (cheatgrass) is an aggressive invasive species posing threats to native ecosystems including increase in fire frequency, alteration of water and nutrient cycles and exclusion of native species. As such, it is important to monitor this species worldwide. However, outside the United States, it has been poorly studied. We studied this species at two scales: (i) at a local scale, evaluating the species presence and its determinants, along the ecotonal area between the steppe and the forest within north-western Patagonia, to reveal whether *B. tectorum* is actually invading natural ecosystems in areas comparable with those invaded in USA, and (ii) at a regional scale, through a search of literature and herbaria databases on *B. tectorum* in South America, to determine the current known distribution of the species in this subcontinent. Results indicate that it is already invading north-western Patagonia in Argentina, mainly in the semi-arid part of the region, and that precipitation influences the invasion process. We found that for South America, *B. tectorum* has been only documented in southern Argentina and Chile. Given the similarities to other invaded regions, the possibility of invasion for Patagonia has been predicted but not prevented. It is important to study changes in the invasion level where it is already established, and to encourage managers with prevention and control strategies. Combining this information with lessons from places with extensive periods of invasion could help to initiate management of the species in areas where the invasion process is beginning and before the species spreads widely.

Keywords: Argentina, cheatgrass, Chile, distribution, habitat, invasive species, Patagonia.

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Introduction

In South America, there is little information on non-native species invading natural ecosystems and publications are mainly focused on the most conspicuous species (Ziller *et al*., 2005; Speziale & Lambertucci, 2010; Speziale *et al*., 2012). Particularly important is the lack of knowledge about species that, although less conspicuous, are known as aggressive invaders in similar environments elsewhere in the world. This is the case with *Bromus tectorum* L. (cheatgrass), a cool-season annual grass, whose frequent small size makes it an inconspicuous species. The native range of *B. tectorum* probably includes large portions of arid Eurasia (Mack, 2011); the grass has subsequently been introduced into Japan, South Africa, Australia, New Zealand, Iceland, Greenland, Canada and the United States (Edgar & Connor, 2000; ISSG, 2012). In

Correspondence: L Speziale, Universidad Nacional del Comahue, Quintral 1250 (R8400FRF), Bariloche, Argentina. Tel: (+ 54) 0294 4423374 (ext. 509); Fax: (+ 54) 4422111; E-mail: karinaspeziale@gmail.com

southern South America, it has been sporadically cited in studies focused on different plant communities, but has not been reported as invading this zone (e.g. Nicora, 1978; Soriano *et al*., 1983; Bradford & Lauenroth, 2006). However, susceptibility to substantial *B. tectorum* invasion has been recently predicted for the southern tip of South America, given that its climatic conditions are similar to invaded areas in western North America (Bradford & Lauenroth, 2006). Introductions of the species into Argentina appear to have been drawn from central or eastern Europe, probably by subsequent waves of human immigration (Novak & Mack, 2001).

Bromus tectorum is an aggressive invader posing enormous threats to native ecosystems. The fine dead biomass produced in summer, after its annual death, increases fire frequency or severity, which damages or even kills native vegetation (D'antonio & Vitousek, 1992). It competes with native species through its root system capturing resources otherwise available for natives, thus reducing their productivity and water status (Melgoza & Novak, 1991). It is also a better competitor in comparison with perennial species, given it exhibits superior germination and growth, especially under low-temperature regimes during autumn, winter or early spring (Hardegree *et al*., 2010). In heavily invaded areas, *B. tectorum* also modifies community composition, reduces amounts of valuable forage, decreases crops survival and alters energy, water and nutrient cycling (e.g. Bradford & Lauenroth, 2006; Miller *et al*., 2013; Orloff *et al.,* 2013). Despite these threats, the distribution of *B. tectorum* and its current invasion status have not been analysed in South America.

Experience of invasions in one area can be useful for predicting where and how a species invades other areas (Richardson *et al*., 2008). In particular, we analysed whether *B. tectorum* is already invading in South America in areas climatically and physiognomically comparable with those invaded in USA (Paruelo *et al*., 1995; Bradford & Lauenroth, 2006). The species is present in northern Patagonia (Bradford & Lauenroth, 2006; Speziale & Ezcurra, 2011). Given that introduced species invading disturbed environments do not necessarily invade native natural communities (Godfree *et al*., 2004), we studied natural environments of the transition between the steppe and the temperate forest to assess whether the species is invading any of these natural communities. We also analysed climatic and anthropogenic determinants of *B. tectorum* presence in these areas. For this, we studied the species presence, along with anthropogenic and climatic characteristics that could determine its presence, through the ecotonal area between the steppe and the forest within north-western Patagonia, to reveal whether *B. tectorum* is actually invading natural ecosystems. We also reviewed published literature in search of studies on *B. tectorum* for the whole of South America, to find if the species is present in other regions of this southern continent.

Materials and methods

Study area

We conducted field work in an area of ca. 15 000 km^2 in north-western Patagonia, Argentina (39°47′–41°27′S and 70°26′–71°32′W; Fig. 1). In this area, precipitation mainly occurs in autumn, winter and spring from April to September and ranges from about 2000 mm year^{-1} to the west, to 300 mm year^{-1} to the east. The western area comprises forest within Argentinean National Parks (Nahuel Huapi and Lanín National Parks). Towards the east, the vegetation opens into shrubland and steppe, extending beyond the protected areas into private land. The region is mainly used for tourism, forestry and cattle and sheep rearing. Several towns and four small cities (*c*. 10 000 to 130 000 people) are found in the region. Important disturbances in the area are anthropogenic fires and grazing by introduced animals (Veblen *et al*., 1992).

Data collection

We travelled the area along five west–east transects of ca. 100 km, along national or provincial roads, traversing all the vegetation types present in the region (Fig. 1). We conducted vegetation samplings during spring and summer 2003–2004, concurrent with the growing season of the regional flora. In total, we established 48 sampling plots 100 m^2 (10 × 10 m; Otýpková & Chytrý, 2006) distributed as 9–10 plots in each transect, placed equidistantly 8 km apart (Fig. 1). We located plots away from bogs and wet meadows, in places that were representative of the local natural vegetation, separated at least 200 m from roads and 10 km from urban settlements, and without recent signs of fire, overgrazing or other anthropogenic disturbances. The plots were classified as forest, shrubland or steppe, based on bibliography, visual examination and previous experience (Cabrera, 1994; Leon *et al*., 1998; Speziale *et al*., 2010). Forest plots (n = 17) were dominated by 1–3 tree species with closed canopies, mostly *Nothofagus* spp. Shrubland plots (n = 9) were open formations dominated by tall shrubs, such as *Schinus patagonica* (Phil.) I.M. Johnst. ex Cabrera, *Lomatia hirsuta* (Lam.) Diels, *Maytenus boaria* Molina and *Discaria* spp. and/or 1–2 tree species, such as *Austrocedrus chilensis* (D. Don) Pic.Serm.

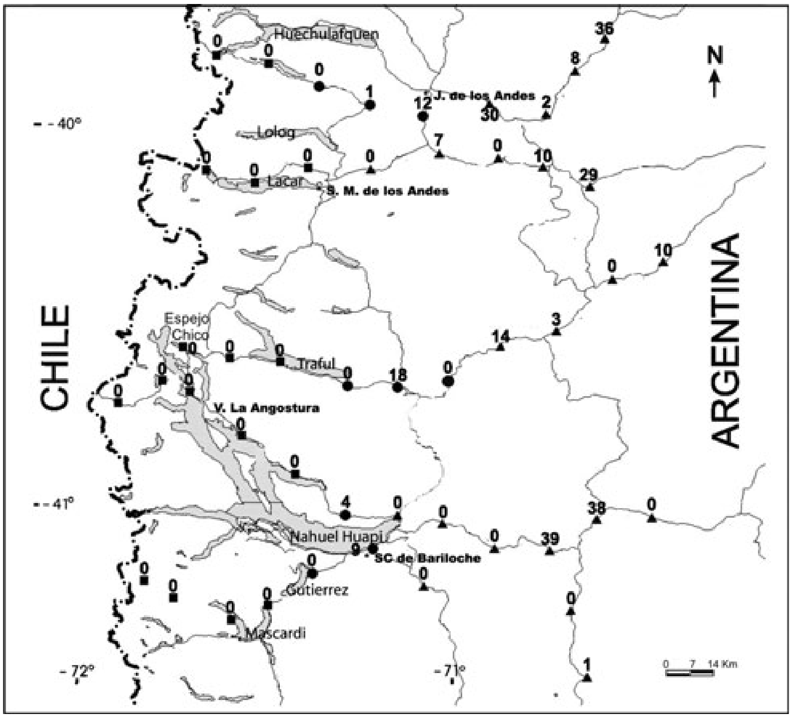

Fig. 1 Locations of sampling plots within the forests (black squares), shrubland (black circles) and steppe (black triangles). Lines represent roads and number over the sample points are cheatgrass percentage coverage.

& Bizzarri or *Nothofagus antarctica* (G. Forst.) Oerst. Steppe plots (n = 22) included both herbaceous and shrubby steppes dominated by tussock grasses, such as *Stipa* (*Pappostipa*) spp., *Festuca* spp. and shrubs such as *Mulinum spinosum* (Cav.) Pers., *Senecio bracteolatus* Hook. & Arn., *Adesmia* spp., or *Anarthrophyllum* spp. (Cabrera, 1994; Leon *et al.*, 1998). In each of the 48 plots, we registered whether *B. tectorum* was present among the native vegetation. We also estimated *B. tectorum* cover per m^2 for each 10 m × 10 m plot by randomly throwing four times a 0.5 m × 0.5 m wood frame subdivided into a 25-celled nylon-string grid, each cell 10 cm^2. In each placement, we estimated the proportion of cells of the grid covered by *B. tectorum* (number of cells covered by *B. tectorum*/25). For example, if we had 14 cells with presence of *B. tectorum* but ten had 100% cover and four were only 50% cover, we considered that we had 12 cells of 100% cover. Then, for each plot, we summed the four cover values and thus calculated total cover per square metre in each plot. In total, we placed 192 grids in the study area.

We also reviewed published literature to obtain information on *B. tectorum* presence in South America (see details on methodology and results in Appendix A).

Analyses

We used logistic regression to analyse which variables were affecting *B. tectorum* presence patterns in north-western Patagonia. For this, we developed two models that we tested separately. Given that climatic conditions have been shown to specify regions that are susceptible to *B. tectorum* invasion, we chose a climatic model (Bradford & Lauenroth, 2006). However, as disturbance regimes appear to dictate how severe the invasion will be (Bradford & Lauenroth, 2006), we also tested a disturbance model. *Bromus tectorum* is a cold-temperate species affected by precipitation that can grow in soil with temperatures approaching freezing (Evans & Young, 1972; Bradford & Lauenroth, 2006; Bradley, 2009; Busso & Bonvissuto, 2009). Therefore, we used mean annual precipitation and maximum annual temperature to analyse the effect of climate. We extracted the values of these variables for each plot from the WorldClim database with a spatial resolution of 1 km^2 (Hijmans *et al.*, 2005). As a measure of anthropogenic disturbance, we estimated distance to the closest city or town using the measuring tool of the Google Earth software. As a measure of abundance of livestock, we counted cattle faeces in each plot. Variables whose effect was significant in each separate model were included in a mixed model. We used Akaike's information criterion (AIC) to rank the models and then selected as the best model, the one that had lowest AIC (with $\Delta AIC < 2$ considered equivalents, Burnham & Anderson, 2002).

Results

Of the 48 plots sampled (17 forest, nine shrubland and 22 steppe), we found the species in 18 plots, 13 of which were in the steppe area of Argentinean Patagonia (Fig. 1). Cover values of *B. tectorum* varied between one and 38% (Mean: 9.95; SD: 13.42). In the steppe habitat, the studied plots received between *c.* 340 and 750 mm of precipitation per year. Within the shrubland area, we found five invaded plots; the one with higher cover had 18% and received around 750 mm of precipitation per year. We did not find the species in any forest plot. Plots in which the species was present were located within two National Parks (Nahuel Huapi and Lanín NP), as well as outside their borders.

The *climate* logistic regression model showed that precipitation had a negative effect and maximum temperature had no significant effect on the presence of *B. tectorum* in the studied area (Table 1). The *disturbance* model showed a positive effect of distance to urban centres (Table 1). The mixed model including both precipitation and distance to urban centres showed that only precipitation had a negative effect on the presence of *B. tectorum* (Table 1). However, the climate model was the best one, because it had a lower AIC than the mixed model (with a difference of more than two units, Table 1). This suggests that the climatic model is better at explaining the presence of *B. tectorum* in the studied plots. Regarding the spatial distribution in South America, this species has been cited as present only in Chile and Argentina (Table A1).

Discussion

Bromus tectorum is currently distributed mostly in the Patagonian region, in the southern tip of South America, an area with similar climate conditions to the invaded region in USA (Soreng *et al.*, 2003; Zuloaga *et al.*, 2008; Speziale & Ezcurra, 2011). In Argentina, it has been collected since the 1930s (Gutierrez & Pensiero, 1998) and is now reported as distributed in up to eight provinces from the centre and the south of this country (Zuloaga *et al.*, 2008). Invasive species are defined as those with individuals dispersing, surviving and reproducing at multiple sites across a greater or lesser spectrum of habitats and extent of occurrence (Blackburn *et al.*, 2011). Our results indicate that *B. tectorum* is already invading at least north-western Patagonia; we found the species growing and reproducing in nearly all the sampled steppe and more than half of the ecotone sites. Our study allowed us to evaluate the actual level of invasion within natural and semi-natural areas of north-western Patagonia, but it is only a partial view of the state of invasion. It should be important to extend the sampling along roads and to other urban areas and sites of disturbance, such as cattle pens, stockyards and areas where livestock are concentrated and from which the grass will likely be dispersed, as cattle are positively associated with the presence of *B. tectorum* (Reisner *et al.*, 2013). Assessing these issues would be a valuable gauge to know if it is dispersing and to forecast the extent it can move further in this new range.

Among characteristics of the environments invaded by *B. tectorum*, precipitation has been reported as an important factor influencing the process of invasion of this species (Evans *et al.*, 1970; Bradley, 2009), and we found this to also be the case in Patagonia. Here, the invasion is mainly within the arid eastern steppe portion of whole study area. This agrees with most studies in North America, given that we found higher invasion levels in the most arid parts of the study area (Mack, 1981; Adair *et al.*, 2008). In the Great Basin, USA, where invasion of this species is most problematic, total annual precipitation ranges from 200 to 400 mm in valleys mostly during winter (Bradley, 2009; Busso & Bonvissuto, 2009). However, we also found it in environments with more than 700 mm annual

Table 1 Logistic multiple regression for three models including climatic variables (precipitation and maximum temperature), anthropogenic disturbance variables (distance to urban centre and cattle faeces) and a mixed model including the best variables from the previous ones for *B. tectorum* presence. Estimations were taken in plots of 10 m × 10 m throughout a vegetation gradient in north-western Patagonia (see methods for more detail; n = 48 plots)

Model	Variable	Coefficient	Std coeff	Std error	t	P	ρ^2	χ^2	P	AIC
Climatic	Constant	−4.36	0	4.46	−0.98	0.33	0.51	29.6	<0.001	34.35
	Precipitation	0.009	−7.54	0.003	−3.05	0.002				
	Maximum temperature	0.07	1.96	0.04	1.46	0.14				
Disturbance	Constant	−3.84	0	1.13	−3.4	<0.001	0.23	12.23	0.001	50.72
	Distance to urban centre	0.07	2	0.03	2.84	0.005				
	Cattle faeces	0.2	1.72	0.1	2.06	0.04				
Mixed	Constant	23.06	0	33.14	0.7	0.49	0.47	27.29	<0.001	36.66
	Precipitation	−0.008	−7.06	0.003	−2.66	0.008				
	Distance to urban centre	0.002	0.07	0.03	0.06	0.95				

precipitation, therefore expanding the area that can supposedly be invaded by this species in relation to precipitation.

Despite its prevalence in arid and semiarid environments, *B. tectorum* biomass generally shows a strong positive relationship with the availability of water in these types of ecosystems (Adair *et al.*, 2008). In the hyperarid Monte of Argentina, a region with <150 mm annual rain, *B. tectorum* has been associated with years of above-average precipitation (Busso & Bonvissuto, 2009). However, we found a negative relationship with precipitation. This result may be influenced by the length of the studied gradient. In our case, precipitation changed from 300 mm per year in the east to 1700 mm per year in the west within the entire study area, perhaps representing an excess of water towards the west that does not allow *B. tectorum* to grow, as has been suggested for other species as well (Speziale *et al.*, 2010). Also, woody species increase throughout the gradient, forming dense forests towards the wetter western areas. Thus, shading might be lowering photosynthesis and restricting its presence in these humid environments (Pierson *et al.*, 1990). To date, studies have not tested the combined effects of these two variables (precipitation and shade) on the presence of *B. tectorum* in the shrubland-forest area. Either or both factors could be responsible for the absence of the species in the forest areas of western Andean Patagonia.

Determinants of invasion success also depend on the interaction between characteristics of the invader and the plant community invaded, including environmental variables, disturbances and species characteristics (Brown & Rice, 2010; Reisner *et al.*, 2013). In Patagonia, perennial species are prevalent and dominant, so an empty niche may favour alien annual species (Ferreyra *et al.*, 1998; Speziale & Ezcurra, 2011). In addition, in Patagonia, perennial species rely on deeper soil water content, given their generally deep root systems (Jobbágy *et al.*, 1996). In the seedling state, *B. tectorum* is a superior competitor, as it has higher rates of germination and requires less time to complete its cycle than perennial species (Blank, 2010). Annual species such as *B. tectorum* also have an advantage over perennials, as they profit from small water inputs of occasional precipitation (Jobbágy *et al.*, 1996; Speziale *et al.*, 2010). Moreover, being a cool-season annual, *B. tectorum* avoids drought during summer, given that adult plants die during late spring and their seeds remain dormant through summer until the first autumn rains. These phenological differences with native species may give *B. tectorum* competitive advantages by depending on spring precipitations that are abundant at the beginning of its growing season (Rice *et al.*, 1992). In consequence, *B. tectorum* outcompetes other plants in regions with consistent water availability in autumn, winter and early spring (Bradford & Lauenroth, 2006), such as found in Patagonia.

The actual distribution of *B. tectorum* in South America is unknown in detail, but current published information (Appendix A) shows that it has been found in temperate latitudes generally south of 35°S (Zuloaga *et al.*, 2008). This is also supported by the reports in the IABIN and the information from the Darwinian Herbarium specimens database (Instituto de Botánica Darwinion (accessed through GBIF, http://datos.sndb.mincyt.gov.ar/portal/datasets/resource/86 25 June 2012, and http://www2.darwin.edu.ar/Herbario/Bases/BuscarIris.asp June 2012). Beyond Argentina, it has also been recorded in four regions of Chile in a similar southern area (VII, IX, XI and XII regions; Zuloaga *et al.*, 2008). Its presence has also been reported for Uruguay, but without locality or voucher and therefore is unconfirmed (Zuloaga *et al.*, 2008). It has not been recorded for northern countries of South America, such as Bolivia, Paraguay, Brazil, Ecuador, Peru, Venezuela and Colombia, whereas there is a lack of information on alien species for French Guiana, Guyana or Suriname (Matthews & Brand, 2005; Ziller *et al.*, 2005; Schüttler & Karez, 2008; Zuloaga *et al.*, 2008). Except for one, none of the studies reporting *B. tectorum* in Argentina or Chile had an *a priori* aim of studying *B. tectorum* (Table A1). This could indicate a lack of particular interest in the species as an invader.

Thirty years after it was reported as a minor component of vegetation and more than eight decades after it was first collected in Argentina (Soriano *et al.*, 1983), *B. tectorum* is invading the southern tip of South America. This spread may be facilitated by its small size, which renders it inconspicuous during the first stages of its invasion and which could also explain the lack of studies on this species outside of North America. However, it is important to focus on this aggressive invader soon, in order to reduce its associated effects on South American environments including, for example, effects on fire regime, nitrogen cycling and the survival of native perennials.

Management recommendations

Management of this species merits special attention to avoid costly remediation in the future (Pimentel *et al.*, 2001). Soil treatments may temporally reduce *B. tectorum* and enhance native species, but they do not completely extirpate this introduced species (Belnap & Sherrod, 2009). Moreover, the wide range of its current distribution makes these treatments very difficult to implement. On the other hand, pulling out *B. tectorum* by hand is effort-intensive and time-consuming and is recommended only for very small infestations. Therefore, studies on methods of controlling reproduction should be encouraged. Our results showing the possible limitations imposed by very low and high precipitation and shading may be helpful in this regard. A basic control approach should involve a monitoring programme to rapidly detect any new incursions of this species elsewhere in South America. Moreover, new introductions should be prevented, particularly to avoid potentially aggressive genotypes (Schachner *et al.*, 2008). It is important to study this species invasion particularly where the environments resemble those already invaded in North America. The combination of the knowledge gained in North America, together with increased research and management strategies in the southern tip of South America, could unveil the impacts of this aggressive species for southern ecosystems, particularly in Patagonia, and help managers act before it continues spreading.

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Appendix A Literature review on the distribution of *Bromus tectorum* in South America.

Materials and methods for the literature review

We reviewed existing literature with a search of ISI Web of Science and Google Scholar to analyse *B. tec-*

torum distribution and extension in South America. We analysed all papers that included this species with information about its presence in South American countries. We also revised two reviews of presence of exotic species for South America (Matthews & Brand, 2005; Schüttler & Karez, 2008) that are not included in the ISI Web of Science. We also used the i3N engine through which South American countries are organising existing data on introduced species within the frame of IABIN (Inter-American Biodiversity Information Network accessed through http://i3n.iabin.net/) and the database of Instituto de Botánica Darwinion on species and herbarium specimens from southern South America (accessed through GBIF, http://datos.sndb.mincyt.gov.ar/portal/datasets/resource/86 25 June 2012, and http://www2.darwin.edu.ar/Herbario/Bases/BuscarIris.asp June 2012).

Annex Table 1 Publications found by conducting a search in the ISI Web of Knowledge and Google Scholar that include the presence of *B. tectorum* in a South American country

Region studied	Aim of the study	Country where B. tectorum was cited	Source
North Patagonia, Argentina and Chile	Study the association of present pollen rain, and current vegetation and climate to provide modern analogues to calibrate fossil records	Argentina	Paez *et al.,* (1997)
Central Argentina (La Pampa province)	Prepare a catalogue of grasses of La Pampa province.	Argentina	Steibel *et al.,* (1997)
Argentina	Prepare a synopsis of the genus *Bromus* (Poaceae)	Argentina	Gutierrez & Pensiero (1998)
North Patagonia, Argentina	Document the effects of nests of the leaf-cutting ant *Acromyrmex lobicornis* on soil properties and their influence on plant diversity	Argentina	Farji-Brener & Ghermandi (2000)
North Patagonia, Argentina	Analyse the influence of refuse dumps of leaf-cutting ants on seedling recruitment	Argentina	Farji-Brener & Ghermandi (2004)
New World	Prepare a catalogue of New World grasses	Argentina and Chile	Soreng *et al.,* (2003)
North Patagonia, Argentina and north-eastern Colorado, USA	Examine how climate and soil influence the soil water conditions needed for *B. tectorum* establishment, and how disturbance and seed availability influence competition with native plants	Argentina	Bradford & Lauenroth (2006)
South of Chile (Torres del Paine National Park)	Prepare an inventory of introduced plants in the Park including invasion status	Chile	Domínguez *et al.,* (2006)
Argentina, Chile, Paraguay, Uruguay and South of Brazil,	Prepare a catalogue of the southern cone vascular plants	Argentina and Chile	Zuloaga *et al.,* (2008)
North Patagonia (Neuquen province), Argentina	Study soil seed bank between vegetation patches	Argentina	Busso & Bonvissuto (2009)
North Patagonia, Argentina	Analyse the response of vegetation to soil amendments	Argentina	Kowaljow *et al.,* (2010)
North Patagonia, Argentina	Describe regional patterns of non-native species richness and their climatic determinants	Argentina	Speziale & Ezcurra (2011)