

# Effects of past and future land conversions on forest connectivity in the Argentine Chaco

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Received: 15 March 2014 / Accepted: 27 December 2014 / Published online: 21 January 2015  
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## Abstract

**Context** Land-use change is the main driver of habitat loss and fragmentation worldwide. The rate of dry forest loss in the South American Chaco is among the highest in the world, mainly due to the expansion of soybean production and cattle ranching. Argentina recently implemented a national zoning plan (i.e., the Forest Law) to reduce further forest loss. However, it is unclear how the effects of past deforestation and the implementation of the Forest Law will affect forest connectivity in the Chaco.

**Objective** Our main goal was to evaluate the potential effect of the Forest Law on forest fragmentation and connectivity in the Argentine Chaco.

**Methods** We studied changes in the extent, fragmentation, and connectivity of forests between 1977 and 2010, by combining agricultural expansion and forest cover maps, and for the future in a scenario analysis.

**Results** Past agricultural expansion translated into an overall loss of 22.5 % of the Argentine Chaco's forests, with deforestation rates in 2000–2010 up to three times higher than in the 1980s. Forest fragmentation and connectivity loss were highest in 1977–1992, when road construction fragmented large forest patches. Our future scenario analysis showed that if the Forest Law will be implemented as planned,

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**Electronic supplementary material** The online version of this article (doi:[10.1007/s10980-014-0147-3](https://doi.org/10.1007/s10980-014-0147-3)) contains supplementary material, which is available to authorized users.

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forest area and connectivity in the region will decline drastically.

**Conclusions** Land-use planning designed to protect stepping stones could substantially mitigate connectivity loss due to deforestation, with the co-benefit of preserving the greatest amount of biodiversity priority areas across all evaluated scenarios. Including scenario analyses that assess forest fragmentation and connectivity at the ecoregion scale is thus important in upcoming revisions of the Argentine Forest Law, and, more generally, in debates about sustainable resource use.

**Keywords** Agriculture expansion · Subtropical dry forest fragmentation · Ecoregional conservation planning · Future scenarios · National Forest Law · Stepping stones

## Introduction

Land-use change is the main driver of habitat loss and fragmentation (Sala et al. 2000; CBD 2010), thereby threatening many species (Barnosky 2008; Ehrlich and Pringle 2008; Vignieri 2014). While some species can persist in fragmented landscapes, or even benefit from fragmentation, many species become more vulnerable because their populations are smaller (Cagnolo et al. 2006), they are more prone to overexploitation (Michalski and Peres 2005; Bennett and Saunders 2010) and edge effects (de Casenave et al. 1995; Gascon et al. 2000), and their capacity to adapt to environmental change is lower (Travis 2003; Brook et al. 2008). Preserving or restoring connectivity is therefore increasingly recognized as a key goal for land-use and conservation planning (Vos et al. 2008).

Understanding how land-use change affects connectivity at the ecoregional scale is particularly important, because many species are endemic at this scale, and ensuring populations' persistence is therefore critical. Yet conservation planners face substantial challenges when managing for ecoregional connectivity. First, many ecoregions are very large or extend across jurisdictional boundaries, and decentralized land-use and conservation planning (e.g., province- or national-scale planning for ecoregions extending into several countries) can have unintended results at the aggregate, ecoregional scale. Second, understanding whether land-

use or conservation policies implemented to maintain or improve landscape connectivity will continue to work out as intended in the future is challenging, given uncertain future land-use patterns (Piquer-Rodríguez et al. 2012; Faleiro et al. 2013). Exploring how land-use change may affect landscape fragmentation and connectivity under alternative future scenarios can be a powerful tool to inform conservation planning, yet such assessments are scarce (Piquer-Rodríguez et al. 2012; Rubio et al. 2012; Ernst 2014a).

South America has recently experienced widespread forest loss (Grau and Aide 2008), especially in the Cerrado and Gran Chaco ecoregions (Olson et al. 2001) which had among the highest deforestation rates worldwide between 2000 and 2010 (Aide et al. 2013; Hansen et al. 2013). Deforestation during this period was predominantly driven by the rapid expansion of agri-business farming, principally soybean and intensified cattle ranching (Zak et al. 2004; Klink and Machado 2005; Gasparri and Grau 2009; Aide et al. 2013). Argentina increased soybean production by 78 % between 2000 and 2010 (Nassar and Antoniazzi 2011). This resulted in considerable soybean and cattle ranching expansion into natural ecosystems (Aizen et al. 2009; Adamoli et al. 2011; Mastrangelo and Gavin 2012; Gasparri et al. 2013). Pressure on remaining forests is likely to remain high, due to increasing global soybean demand (Lambin and Meyfroidt 2011; Reenberg and Fenger 2011; Diogo et al. 2014).

Deforestation threatens the rich biodiversity of the Argentine Chaco, which includes 145 mammal species (12 endemic), 409 birds (7), 54 reptiles (17), 34 amphibians (8), and more than 80 plant genera (3,400 species, of which 400 are endemic) (Bucher and Huszar 1999; Giménez et al. 2011). The Chaco is also a globally significant carbon pool (Gasparri et al. 2008). Yet, only a few studies have so far assessed forest loss and fragmentation in the Argentine Chaco, generally focusing on small regions (Zak et al. 2004; Grau et al. 2005b; Boletta et al. 2006; Grau and Aide 2008; Zak et al. 2008; Gasparri et al. 2010; Volante et al. 2012; Torrella et al. 2013) or relatively short time periods (Clark et al. 2010; Portillo-Quintero and Sánchez-Azofeifa 2010; Aide et al. 2013; Caldas et al. 2013; Hansen et al. 2013).

Concern about protecting remaining native forests in the Argentine Chaco led to a national Forest Law, passed in 2007 (*Ley de Presupuestos Mínimos de Protección Ambiental de los Bosques Nativos* 26.331). The Forest Law zones forest areas into three different classes of

land-use restrictions: class 1 (‘red zones’) allows no commercial use; class 2 (‘yellow zones’) allows only sustainable uses; and class 3 (‘green zones’) allows most land uses, including deforestation for agricultural expansion [for more details see Seghezze et al. (2011) and García Collazo et al. (2013)]. The Forest Law was planned in a decentralized way (i.e., each province developed their own zonation and implementation framework) and large spatial discrepancies exist when comparing provincial plans (see Fig. 1).

The potential effect of the Forest Law on forest connectivity at the ecoregion scale has neither been considered nor assessed. A better understanding of how current implementation of the Forest Law may affect the Chaco’s forests is therefore important for informing regional planning. Our main goals were to evaluate past and potential future changes in the extent, fragmentation, and connectivity of forests in

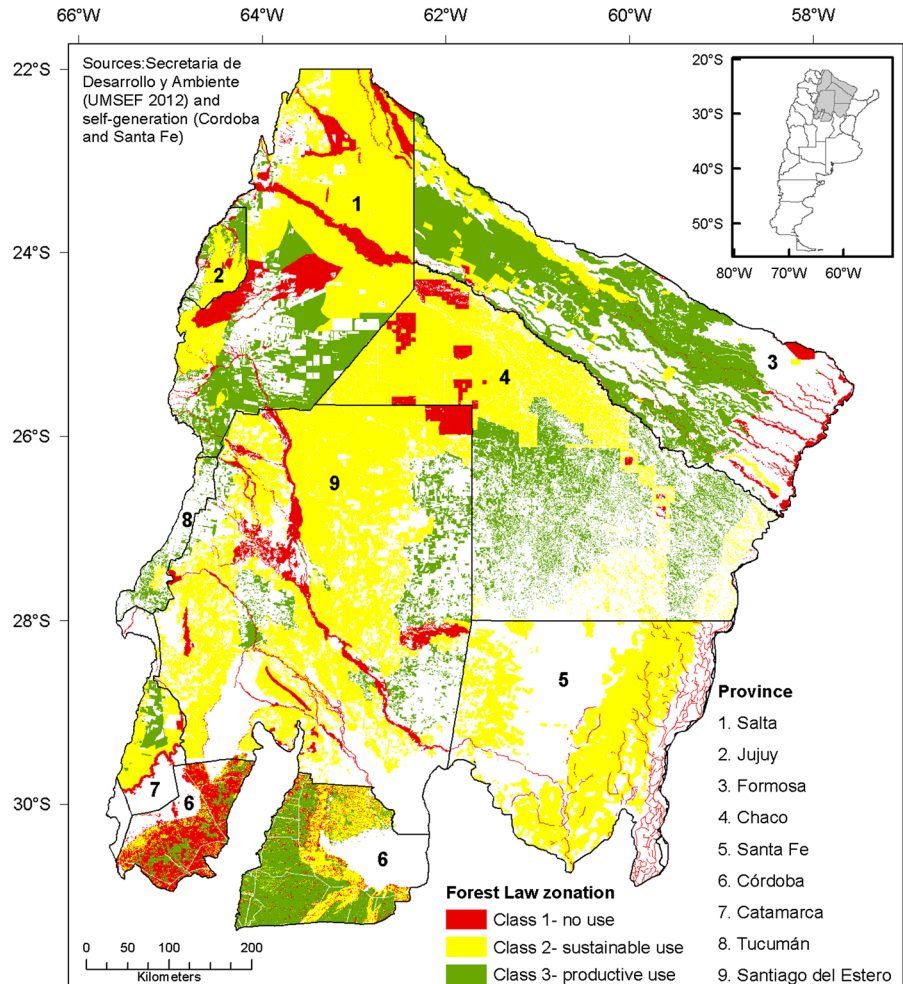
the Argentine Chaco. Specifically, our research questions were:

- (1) What was the influence of past deforestation on forest extent, fragmentation, and connectivity in the Argentine Chaco?
- (2) How will forest extent, fragmentation, and connectivity of the Argentine Chaco develop if the deforestation allowed under the Forest Law takes place?
- (3) What would be the potential effect of ecoregional conservation strategies to mitigate further loss of forest connectivity?

### Study area

The Gran Chaco is a large, dry forest region covering about 1,080,000 km<sup>2</sup> in Argentina (60 % of the Gran

**Fig. 1** Location of study area within the Dry and Wet Chaco and the current zonation of the Argentine Forest Law [we excluded the small mountainous Chaco, Brown and Pacheco (2006)]. Class 3 (green) allows commercial uses of the forest, including its conversion to agriculture. Class 2 (yellow) allows sustainable forest uses, and class 1 (red) fully protects forests except for the province of Córdoba, where exceptions are possible. White background color stands for non-forested areas and forests that were not zoned (Collazo et al. 2013)



Chaco), Bolivia (11 %), Paraguay (28 %), and Brazil (1 %) (Olson et al. 2001). The climate is semi-arid and highly seasonal, with a distinct dry season in autumn and winter (May–September), and a warm, wet season in spring and summer (November–April). Mean annual temperature is  $\sim 22$  °C, with an average monthly maximum of 28 °C (Minetti 1999). Annual precipitation ranges from 1,200 mm in the east (wet Chaco) to 450 mm in the west (dry Chaco). Elevation varies marginally except for the west and southwest of the study area where more hilly terrain prevails. Natural vegetation in the Chaco consists of closed forest, open woodlands, shrublands, and palm savannas. Forests are the most characteristic vegetation formation and are typically dominated by species of the genera *Schinopsis* and *Aspidosperma* (“quebrachos”) (Prado 1993). Here, we focus on the entire Argentine Dry and Wet Chaco, except for the small mountainous Chaco areas (Brown and Pacheco 2006) (Fig. 1).

Traditionally, the dominant land use in the Chaco has been subsistence agriculture and extensive cattle ranching in so-called *puesto* (small homestead) systems (Grau et al. 2008). Recently, native forest and *puesto* systems have increasingly been replaced by agri-business farming, mainly for growing cash crops such as soybeans, sugarcane, maize, and cotton (Grau et al. 2005a; Volante et al. 2006; Grau et al. 2008; Adamoli et al. 2011). Likewise, low-intensity grazing and natural forests are increasingly being replaced by intensive silvopastoral systems that clear the understory and plant exotic, more productive grasses (e.g., *Cenchrus ciliaris* or *Panicum maximum*) (Macchi et al. 2013).

## Materials and methods

### Datasets used

We used base maps of forest cover generated from satellite-based maps of agricultural (cropland and pasture) extent and expansion (available from Adamoli et al. 2011) and a natural vegetation map (SAyDS 2007). Agricultural extent and expansion were digitized from Landsat imagery for the base years 1977, 1992, 2002 and 2010 with a minimum mapping unit (MMU) of 0.02 km<sup>2</sup> (Adamoli et al. 2011). Because these maps did not provide information on forest extent, nor on the type of vegetation replaced by

agricultural expansion, we used the Argentine forest inventory map together with ancillary data (roads and rivers) to derive forest maps for the base years. The National Forest Inventory map (SAyDS 2007) is a base map of natural vegetation at a scale of 1:100,000 produced from 1997 Landsat image interpretation using a MMU of 0.1 km<sup>2</sup>, distinguishing 20 vegetation classes, including forests, shrubs, and grasslands. We reclassified this map into a forest (i.e., all woody vegetation) and non-forest map (Table 1). We included shrublands and open woodlands in our woody-vegetation definition because they constitute important types of natural vegetation in the Chaco as a whole (Táلامo et al. 2012).

To reconstruct forest/non-forest maps for 1977 and 1992, we reclassified all agricultural expansion in the periods 1977–1992 and 1992–2002 as forest for the respective base year with a MMU of 0.1 km<sup>2</sup>. To reconstruct the forest/non-forest maps for 2002 and 2010, we simply erased the agricultural expansion area for each period from the forest inventory map. We also erased 100 m around main roads of 1985 and 2005, and along main rivers to account for road margins and river widths that were not captured in the maps (SIG250, <http://www.ign.gob.ar/sig#descarga>).

As study region boundaries, we used province boundaries from the Database of Global Administrative Areas ([www.gadm.org](http://www.gadm.org)). Because forest patches can extend beyond national boundaries, we extended our study area by a buffer of 20 km to avoid distorting effects in the fragmentation and connectivity analyses (e.g., larger forest patches split into several smaller ones, etc.). The 20-km buffer was selected because it roughly represents the diameter of the home range of the two most wide-ranging apex predators in the Chaco, the puma (*Puma concolor*) and the jaguar (*Panthera onca*) (Canevari and Vaccaro 2007). To extend our forest/non-forest maps into these buffer areas, we used forest maps for Bolivia (SAB 2001) and Paraguay (The Global Land Cover Facility 2006). These maps were static, but deforestation in our study period there was negligible (Killeen et al. 2007; Huang et al. 2009; Hansen et al. 2013).

To assess how past and future deforestation affect conservation priority sites, we used the “*Conservation Portfolio of Priority Areas for Biodiversity*” (TNC 2005) generated at a scale of 1:750,000 for the entire Gran Chaco (Fig. S1, Supplementary Material). Using multi-criteria analyses and targeted workshops,

**Table 1** Woody vegetation types of the Argentine Forest Inventory reclassified as forest habitats for our study (closed and open woodland or shrubland) and the percentage of each vegetation type under each class of the forest law zonation

Forest inventory description	Forest habitats	Forest Law categories (area %)		
		One-Red	Two-Yellow	Three-Green
Tall and dense Quebrachal	Closed woodland	1.0	1.2	0.7
Predominance of Quebracho colorado and Blanco	Closed woodland	15.2	27.1	27.2
Quebrachal with discontinuous cover	Open woodland	17.6	20.1	8.7
Quebrachal and other valuable species	Closed woodland	1.2	4.2	8.7
Open quebrachal and other species	Open woodland	0.1	1.4	0.3
Riparian clustered forest	Open woodland	1.8	0.5	0.1
Islet forest	Open woodland	0.1	0.2	0.5
Dominance of Vinal, Mistol or Itin	Open woodland	3.3	4.5	11.1
Bushes with Horco-Quebracho	Shrubland	1.1	0.1	0.2
Forest cover of 50–74 %	Closed woodland	0.0	0.0	0.0
Forest cover of 25–49 %	Open woodland	0.6	0.6	0.5
Forest cover of 10–24 % (minus agriculture)	Open woodland	1.1	1.3	4.7
Low bushes and herbaceous plants	Shrubland	3.6	6.4	5.2
Bushes with or without few trees	Shrubland	5.8	7.2	3.8
Plains with herbaceous plants and bushes	Shrubland	0.0	0.0	1.3
Salty complexes				
Banyados (halophytic vegetation)				
Natural pastures				
Esteros (partly flooded)				
Hidrophylic herbaceous vegetation				

experts on Chaco wildlife, conservation, and ecology from Argentina, Paraguay, and Bolivia outlined (1) so-called *Areas of Biodiversity Significance* (ABS) for each major taxa (birds, amphibians and reptiles, mammals, and vegetation and plants) based on their regional knowledge and (2) defined conservation planning goals for the Chaco (e.g., minimum area for certain ecosystems). Based on both, experts then established priority areas within the ABS that should be protected to reach the identified conservation goals and that, at the same time, were particularly threatened considering current human pressure (TNC 2005).

#### Mapping past forest change, fragmentation, and connectivity

We calculated forest area change for 1977–1992, 1992–2002, and 2002–2010. To assess forest fragmentation we used Morphological Spatial Pattern Analysis (MSPA, Vogt et al. 2007). MSPA segments a

binary forest/non-forest map into five fragmentation components (Soille and Vogt 2009): core, bridge (i.e., connections among core areas), islet (i.e., small patches without core forest), edge, and perforation (i.e., edge inside core patches). We calculated forest fragmentation maps for each base year (using an eight-neighbour rule and a one-pixel edge), summarized fragmentation components, and calculated change between the fragmentation maps. Additionally, we calculated the degree of fragmentation in percent, based on entropy theory. Minimum values for this measure are reached when the forest cover is a single compact patch, while maximum values are reached when the number of patches is the maximum possible and patches are dispersed over the entire study region (Vogt 2014).

We assessed potential forest connectivity by calculating the proximity index (PROX) and the connectance index (CONNECT) (McGarigal et al. 2012) for the forest/non-forest maps. These two metrics have

been shown to perform well and complement each other in measuring landscape connectivity and fragmentation (Wang et al. 2014). To parameterize these indices, we used the diameter of the home ranges of intermediate dispersers in the Argentine Chaco (i.e., 2 km, Canevari and Vaccaro 2007) as a proxy for the maximum distance between patches that we considered connected. Home ranges are related to dispersal distances (Bowman et al. 2002) and are often used in connectivity analyses to establish movement distances (O'Brien et al. 2006; O'Farrill et al. 2014; Schumaker et al. 2014). Intermediate dispersers benefit most from connecting elements at the landscape scale (Rubio and Saura 2012) and some examples are the giant armadillo (*Priodontes maximus*), the giant anteater (*Myrmecophaga tridactyla*), and the collared peccary (*Pecari tajacu*), all of which are of conservation concern in the Chaco (Tognelli 2005). Thus, our connectivity analyses combined elements from both structural (i.e., landscape structure) and functional (i.e., species-focused) connectivity analyses to study potential connectivity [sensu Calabrese and Fagan (2004), Ernst (2014b)].

The PROX index (Eq. 1) calculates Euclidean distances among patches that are within a specific search radius, in our case forest patches located at a maximum distance of 2 km from the focal patch, while taking into account the size of neighboring patches:

$$\text{PROX} = \sum_{s=1}^n \frac{a_{js}}{h_{js}^2} \quad (1)$$

where  $a_{js}$  refers to the area of patch  $js$  within a specified search radius (2 km in our case) of patch  $j$ ;  $j$  refers to the  $j$ th focal patch and  $s$  refers to the  $s$ th neighboring patch within the search radius of patch  $j$ ;  $h_{js}$  is the distance between the patch  $js$  and the focal patch, based on edge-to-edge distance (McGarigal et al. 2012). PROX thus assigns higher values to patches that are surrounded by many and/or bigger patches, and is preferable over indices that are not area-sensitive (Bender et al. 2003; Fahrig 2013). Since PROX is calculated at the patch level, we also calculated the mean PROX (i.e., PROX\_MN) for each of our maps.

The CONNECT index (Eq. 2) calculates the proportion of functional joins in the entire landscape given our threshold radius of 2 km (McGarigal et al. 2012):

$$\text{CONNECT} = \frac{\sum_{j \neq k}^n c_{jk}}{\frac{n_j(n_j-1)}{2}} (100) \quad (2)$$

where  $c_{jk}$  equals the joining between patch  $j$  and  $k$  ( $0 =$  unjoined,  $1 =$  joined), and  $n$  equals the number of patches in the landscape. CONNECT equals or is close to zero when the landscape is composed of a single patch or none of the forest patches are connected, and equals 100 when all patches are connected (McGarigal et al. 2012).

As a sensitivity analyses, we performed the connectivity analysis at different MMU scales of 0.05, 0.1 and 0.2 km<sup>2</sup> and our results were not sensitive to the MMU size. Furthermore, we evaluated the sensitivity of our connectivity results to the selected home range diameter.

Future forest change, fragmentation, and connectivity

To evaluate how the implementation of the Forest Law may influence future forest fragmentation and connectivity in the Chaco, we assessed three sets of scenarios differing in the assumed amount of forest conversion (Tables S1 and 2). Each province specifies a range of forest conversion that can take place in each zone (e.g., 20–60 % in green zones in Formosa), sometimes according to some spatial attributes such as slope (e.g., Salta), plot size (e.g., Chaco) or land-use zonation (e.g., Formosa). Because we were interested in the potential full impact of implementing the Forest Law, we chose the maximum conversion limit specified per province by law as a basis to calculate deforestation amounts for different conservation strategies. Conversion amounts in our scenarios are thus alternative assumptions of how the future may unfold, and should not be interpreted as forecasts of forest loss.

The first base scenario (scenario 1) assumed that all areas assigned for conversion in green zones per province, according to the maximum conversion limits permitted by the Forest Law, will actually be deforested (Table S1). A second base scenario (scenario 2) assumed that all areas assigned for conversion in green and yellow zones per province, according to the maximum conversion limits permitted by the Forest Law, will be deforested. The case of Cordoba is an exception because conversions can also take place in

red zones (Table S1). This scenario represents a worst-case where conversions take place in green and yellow zones as currently planned (UMSEF 2012). We refer to this scenario as “planned implementation of the Forest Law”. Finally, a third base scenario (scenario 3) assumed that green and yellow zones will experience deforestation following annual deforestation changes of the last 20 years and up to the maximum conversion limits permitted by the Forest Law (see “Past forest change, fragmentation, and connectivity” section and Table 2).

Each of these three base scenarios were calculated in three versions: (a) without additional conservation measures, (b) assuming the protection of the biggest forest patches (Almeida-Gomes and Rocha 2014) and (c) assuming additional protection of small patches, potentially acting as stepping stones (Saura et al. 2013). The protection of big patches required that at least 70 % of the biggest patches to be preserved to avoid potentially non-linear and strong increases in population declines and extinction risk (Fahrig 2003; Swift and Hannon 2010; Camargo Martensen et al. 2012). To define the biggest patches we evaluated the distribution of patches’ area and selected the 20 biggest patches, each with an area greater than 1,670 km<sup>2</sup>. The more restrictive conservation strategy (strategy c) preserved all stepping stones identified as important, as well as a minimum of 60 % of the area of the biggest patches (Table 2). To define potential stepping stones, we arbitrarily choose the patches within the top 10 % of PROX index values among patches not considered “big”. We also limited deforestation to be 25 % lower than conversions allowed in the Forest Law and to preserve a minimum of 40 % of the 2010 forest cover to avoid accelerated extinction (Andren 1994; Fahrig 2003; Villard and Metzger 2014), even if the Forest Law would allow for higher conversion limits (Table S1).

This resulted in three base scenarios (1–3) and three conservation strategies (a: no protection, referred to as *np*; b: protection of big patches only, *pb*; c: protection of big patches and stepping stones, *ps*) and thus a total of nine scenario runs. Scenarios were derived using two alternative allocation procedures: random and systematic. First, we used a tenfold random assignment of deforestation plots until the target deforestation amount per province was reached. To allocate deforestation plots, we generated squared grids with a cell size equal to the median parcel size of the agricultural plots per province, ranging from 0.48 to 5.3 km<sup>2</sup> (INDEC 2002). Second, the systematic allocation scheme assumed deforestation to only occur at the agricultural frontier. We assumed that plots closer to settlements and infrastructure would have a higher chance to be converted to agriculture because demographic dynamics and access to markets are important drivers of deforestation worldwide (Carr 2004; Müller et al. 2011). We used the same plots as above and calculated Euclidean distances per plot to the nearest settlements with >100 inhabitants (localities and cities, SIG 250). Those forested plots closest to settlements were selected for conversion until the specific conversion amounts per scenario and province were reached (Table 2). The choice of these spatial allocation procedures was based on visually inspecting past deforestation patterns, suggesting that both gradual deforestation frontiers as well as leap-frogging processes take place in the study region. We then used the resulting binary forest/non-forest maps to calculate fragmentation and connectivity measures as detailed in the previous section. Furthermore, we derived the average and standard deviation share of fragmentation components across the 10 replicate runs for each scenario (only random allocation scheme).

**Table 2** Deforestation amounts (km<sup>2</sup>) implemented under each scenario

	Scenario 1		Scenario 2		Scenario 3	
	Random	Systematic	Random	Systematic	Random	Systematic
NP	46,964	46,967	158,879	149,954	46,919	46,924
PB	23,215	23,189	69,658	70,384	41,800	43,947
PS	19,515	19,480	47,182	48,518	27,460	26,350

Random and systematic (distance to human settlements) stands for the type of allocation scheme of each scenario type

*NP* No protection, *PB* protection of big patches only, *PS* protection of big patches and stepping stones

## Past and future forest loss in priority conservation areas

We compared the past and future forest cover maps with the priority conservation areas identified in the only broad-scale conservation planning exercise carried out for the Chaco so far (TNC 2005). We summarized forest conversion for the total set of priority areas (i.e., including all priority areas for terrestrial and aquatic ecosystems, birds, amphibians, reptiles, mammals, and vegetation communities) and the terrestrial-only priority set because we specifically studied in-land processes.

## Results

### Past forest change, fragmentation, and connectivity

The Chaco experienced a dramatic acceleration in deforestation since the start of our study period in 1977 (Fig. 2). During both 1977–1992 and 1992–2002, about 20,000 km<sup>2</sup> were deforested, while almost 40,000 km<sup>2</sup> were deforested in 2002–2010. This equals a rate of roughly 4,750 km<sup>2</sup>/year (>0.5 km<sup>2</sup>/h) over the last decade—more than double the rates from the 1990s and more than three times the rates from the 1980s. Our deforestation maps highlighted agricultural expansion frontiers especially in the surroundings of Las Lajitas (Salta Province), Tucuman, Charata (Chaco), Quimili and Bandera (Santiago del Estero) and west of Cordoba. Deforestation tended to occur both along agricultural frontiers and in a more random, leapfrogging way (e.g., in Salta and Formosa Provinces, Fig. 2).

Provincial borders of the zonation map of the Forest Law often mark strong inconsistencies in zoning, such as in the case of the border between Salta and Chaco, where forests classified as green and yellow are adjacent, or between Chaco and Santiago del Estero (yellow and red, respectively, Fig. 1). Yellow zones (sustainable uses) cover by far the greatest area (170,000 km<sup>2</sup>), followed by green zones (all uses, 80,000 km<sup>2</sup>), and red zones (no use, 36,000 km<sup>2</sup>). The *quebrachales* was the dominant vegetation type of the forest inventory protected by the Forest Law (34 % of red zones), but also the most dominantly assigned to

sustainable development (48 % of yellow zones) and potential deforestation (37 % of green zones, Table 1). About 2,800 km<sup>2</sup> (2.5 %) of forest conversions took place in red zones since the implementation of the forest law (AGN 2014), mostly in Cordoba (1,900 km<sup>2</sup>), Salta (300 km<sup>2</sup>), Santiago del Estero (260 km<sup>2</sup>), and Santa Fe (235 km<sup>2</sup>).

As a result of deforestation between 1977 and 2010, edge forest increased by 8.2 % and the number of forest patches increased from ~8,000 patches in 1977 to ~15,000 patches in 2010. Bridge forest decreased strongly throughout the period studied, especially in 1977–1992, when many bridges became isolated or were deforested (Fig. 3). The degree of fragmentation increased accordingly from 1977 to 2010 (Fig. S2).

Landscape connectivity (CONNECT index) decreased by 27 % from 1977 to 2010 (Fig. 4). Connectivity at the patch level, as measured by the average PROX, decreased by 95 % from 1977 to 2010 (Fig. 4). The strongest decline in connectivity occurred in 1977–1992 (Fig. 4). This is in accordance with the high loss of bridges and an increase in edge forest for the same time period (Fig. 3).

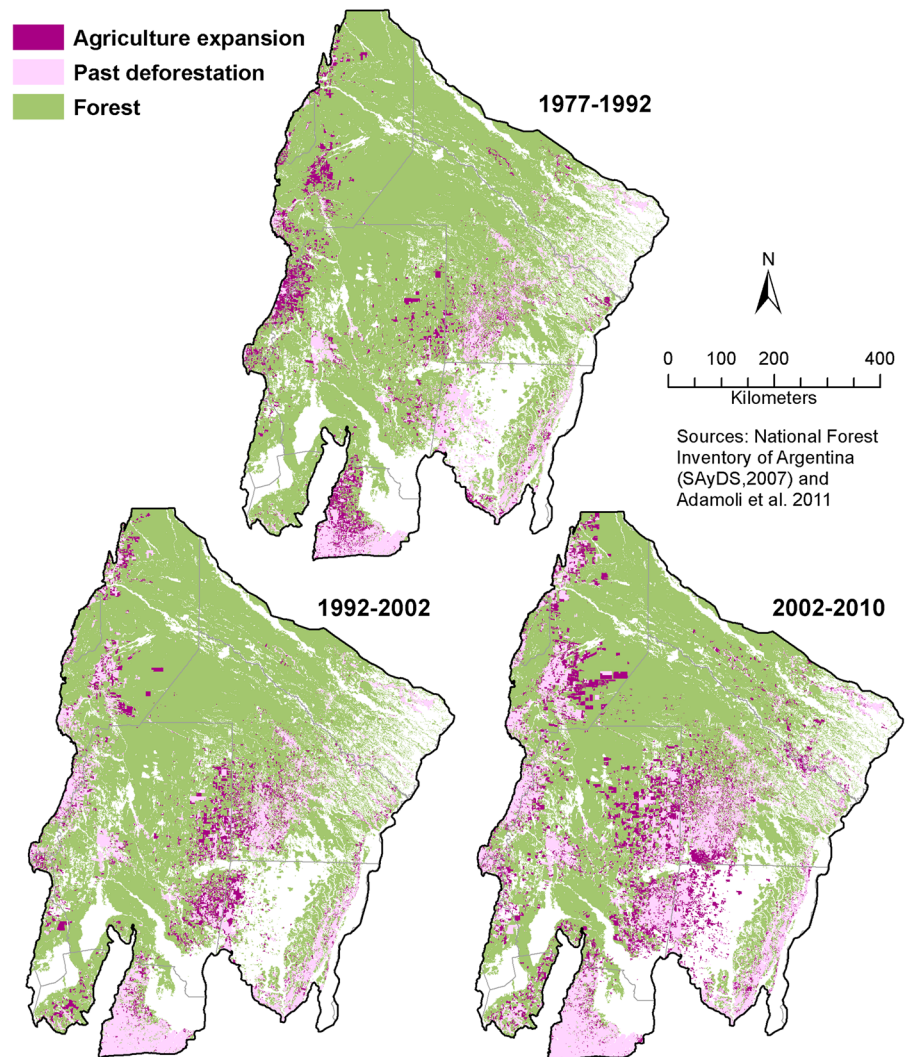
### Future forest change, fragmentation and connectivity

Our future scenarios showed substantial forest loss, which varied among scenarios depending on the assumptions about the amount of deforestation (Fig. 5; Table 2). Should deforestation foreseen in the Forest Law only occur in green zones (scenario1\_np), forest cover will shrink to only 65 % of the level at the end of the 1970s, or to 37 % if deforestation occurs in green and yellow zones (scenario2\_np). If deforestation patterns follow trends from 1992 to 2010 (scenario3\_np), forest cover will fall to 65 % of the extent in the late 1970s.

Our conservation strategies would lead to the preservation of 71 and 72 % of 1970s-level forest for both conservation strategies protecting big patches only, and big patches and stepping stones, respectively under scenario 1. For scenario 2, 59 and 64 % of the late 1970s-level forest would be protected by the strategies protecting big patches only, and big patches and stepping stones, respectively. For scenario 3, 67 and 68 % of the late 1970s-level forest would be



**Fig. 2** Forest maps derived from the National Forest Inventory of Argentina (SAyDS 2007) and agricultural expansion data (Adamoli et al. 2011). Agriculture area in 1977 is used as the baseline

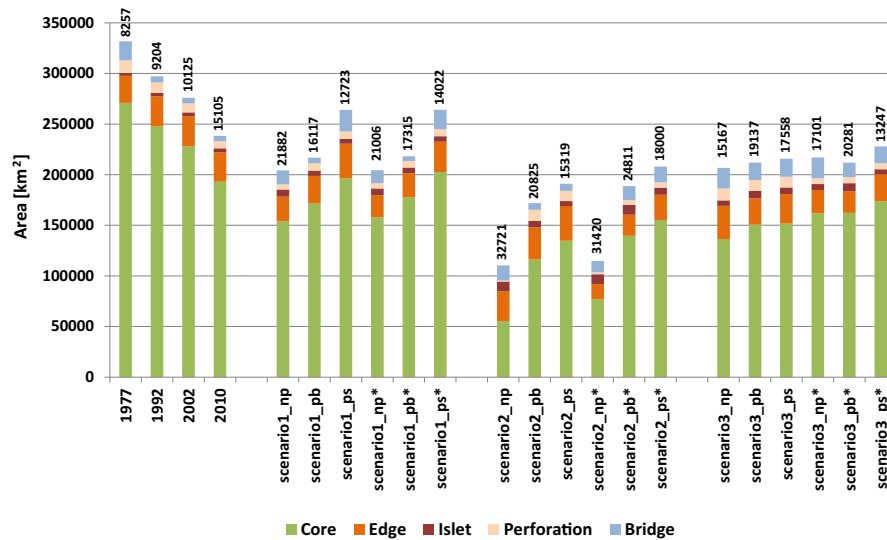


protected by the strategies protecting big patches only, and big patches and stepping stones, respectively.

Analyzing future forest fragmentation showed that the implementation of the Forest Law in green zones under the protection of big patches and stepping stones (scenario1\_ps\*) would translate into the preservation of the highest amount of core forest (202,700 km<sup>2</sup> with 14,000 patches) across all scenarios (Fig. 3). Fragmentation would be highest for scenario2\_np, with a large increase in the number of patches (32,700), bridge forests (14,900 km<sup>2</sup>) and island forests (9,400 km<sup>2</sup>), and the lowest core area (104,000 km<sup>2</sup>) among all scenarios. Conversely, extrapolating historic deforestation trends while protecting big patches and stepping stones (scenario3\_ps\*, Fig. 3) would also

lead to one of the lower forest fragmentation scenarios [core area: 174,000 km<sup>2</sup>, 13,247 patches (Fig. 3)]. Fragmentation components varied only marginally among the tenfold runs.

The degree of fragmentation was lower for scenario 1 but increased markedly for scenarios 2 and 3. Among these two scenarios, following a random allocation scheme resulted in higher degrees of fragmentation (Fig. 5). The east of the Chaco experienced the highest degree of fragmentation for all scenarios due to the spatial distribution of forest in small fragments (i.e., on non-flooding areas) and to historically smaller agricultural fields in this area. The lowest degree of fragmentation was located in the northwest of the region, where big forest patches are situated.



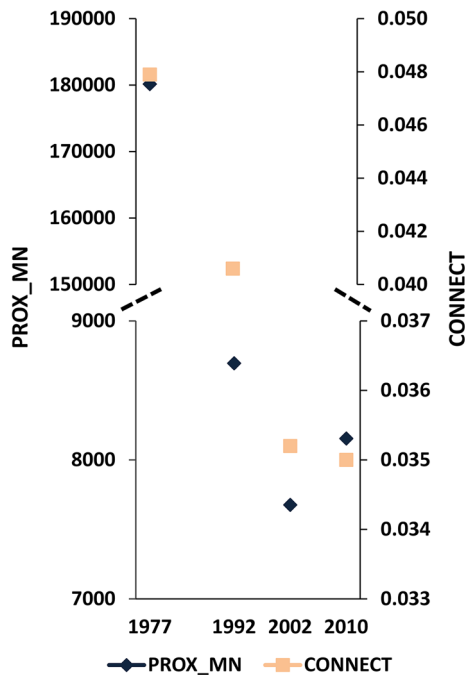
**Fig. 3** Extent of forest in different fragmentation classes for the past and for the future scenarios. Numbers on top of the columns are the number of forest patches in the landscape. np = no protection, pb = protection of big patches only, ps = protection of big patches and stepping stones. Scenario 1 allows conversions in green zones, scenario 2 allows conversions in

green and yellow zones and scenario 3 allows conversions in green and yellow zones following historic deforestation amounts. Scenarios marked (asterisk) used a systematic allocation scheme for deforestation (distance to human settlements)

Evaluating forest connectivity under alternative future scenarios showed that preserving big patches and stepping stones would maintain the highest connectivity when assuming lower amounts of deforestation. The overall highest landscape-level connectivity would be preserved for the scenario assuming deforestation in green areas under the protection of big patches and stepping stones (scenario1\_ps\*, Fig. 6). Overall, preserving both big patches and stepping stones was the conservation strategy that maintained the highest degree of connectivity across all three conservation strategies, including when deforestation amounts were comparable among strategies such as in the case of (1) scenario2\_ps\*, scenario1\_np\* and scenario3\_pb\* or (2) scenario1\_ps\*, scenario3\_ps\* and scenario1\_pb\* (Fig. 6). The strongest decrease in connectivity occurred under the currently planned implementation of the Forest Law (scenario2\_np\*), that is if green and yellow zones are not protected in addition to what is currently foreseen in the Forest Law (Fig. 6). However, the protection of big patches and stepping stones under this scenario (scenario2), would result in a substantial connectivity increase, despite relatively high amounts of deforestation (Fig. 6).

Past and future forest loss in priority areas for conservation

Comparing past and future deforestation scenarios with the TNC conservation priority areas showed that in 2010, 45 and 55 % of the proposed final and terrestrial sets of priority areas, respectively, were still forested. The Forest Law fully protects only 15 % of these priority areas (i.e., in red zones), while 55 % can be sustainably used (i.e., yellow zones) and ~25 % are in green zones without use restrictions. The highest share of priority areas preserved among our scenarios occurred when big patches and stepping stones were protected and deforestation rates were not higher than in the past 20 years (scenario3\_ps\*, 95 % of the 2010 forest in the final set and 98 % in the terrestrial set preserved). In contrast, the lowest remaining forest area within priority areas occurred for the planned implementation of the Forest Law (scenario2\_np, 52 % of the 2010 forest in the final set and 39 % in the terrestrial set preserved). Protecting big patches and stepping stones for this scenario would have a substantial effect, with 88 and 86 % of the 2010 priority-area forest preserved for the final and terrestrial set respectively. The scenario where deforestation



**Fig. 4** Connectivity indices at the patch (PROX\_MN, MN = mean) and landscape (CONNECT) levels for the past study period. PROX index values are unit less and increase as patches become closer and are more contiguous (or less fragmented) in distribution and vice versa. CONNECT index: equals or is close to zero when the landscape is composed of a single patch or none of the forest patches are connected. This index equals 100 when all patches are connected. In our case, values are quite low because the landscape is composed of few, very big, well-connected patches and many small, poorly-connected patches

would only occur in green areas while protecting big patches and stepping stones alike (scenario1<sub>ps\*</sub>) would also preserve 93 and 94 % of the 2010 priority-area forest for the final and terrestrial set respectively.

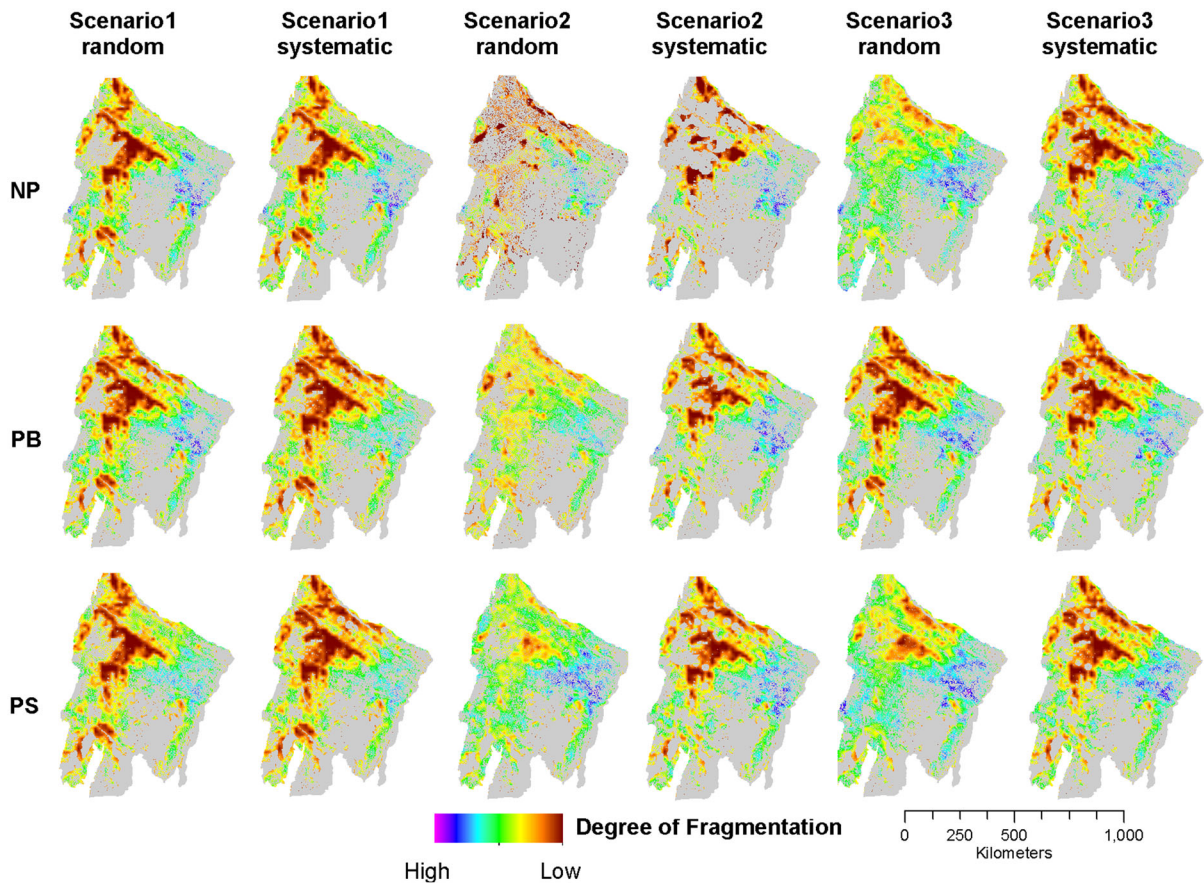
## Discussion

Compiling the provincial zoning plans for the Forest Law into an ecoregion layer clearly showed strong inconsistencies between provinces, including the same forest patch assigned to high-conservation value in one province (e.g., Santiago del Estero), but to potential deforestation in the neighboring province (e.g., Chaco). Moreover, our analyses showed that frameworks for how the Forest Law is implemented vary starkly between provinces. The provincial zoning maps were

produced in different years and by differing institutions and stakeholders (i.e., universities, consultants, governmental departments, etc.). Provinces also interpreted and regulated the national Forest Law differently (Table S1). For example, up to 90 % of forests in green zones can be deforested in Chaco province, whereas Formosa allows deforestation only up to 60 % in the same zone. Similarly, red zones in Cordoba can be converted to some extent whereas red zones are strictly protected in all other provinces. These examples highlight the difficulties planners face in managing for forest connectivity at the ecoregion scale, and strongly suggest that provincial-level planning should be complemented by a broad-scale assessment of connectivity in upcoming revisions of the Forest Law.

We also found marked losses of high-conservation-value forest prior to the implementation of the Forest Law in areas that were later designated as red zones (where deforestation is prohibited), for example, in the provinces of Salta, Santiago del Estero and Santa Fe (AGN 2014). Our results cannot attest to whether this deforestation occurred illegally. Deforestation might have been approved before the sanctioning of the law, yet there was a time window when future zoning was clear, but the Forest Law was not yet fully implemented (Gasparri and Grau 2009; Seghezzo et al. 2011). The outcomes of the Argentine Forest Law to date, with increasing forest loss before the implementation of the law and continued fragmentation thereafter, are unfortunately not uncommon and resemble cases of increased forest loss prior to the implementation of nature protection in Brazil (Hardt et al. 2013) and Eastern Europe (Kuemmerle et al. 2007; Knorn et al. 2012). However, the Forest Law also undoubtedly had positive effects and lowered deforestation during the moratorium on land conversion issued by the Argentine government (2005–2006), when deforestation rates decreased in some provinces (Seghezzo et al. 2011).

The widespread and strongly-accelerating deforestation we documented resulted in a substantial increase in forest fragmentation and a loss of potential connectivity from 1977 to 2010 (Figs. 3, 4). The particularly strong increase in fragmentation between 1977 and 1992 was likely due to widespread road building (e.g., Ruta 81) during that time (Ernst 2014a). Further fragmentation was caused by a lack of coordinated planning and scattered conversion



**Fig. 5** Scenarios of future forest extent and fragmentation degree for different levels of implementation of the Forest Law. NP = no protection, PB = protections of big patches only, PS = protection of big patches and stepping stones

patterns that are a result of the small-scale ownership structure of the post-colonial smallholders' system (Adamoli et al. 2011). Together, this translated into the widespread creation of edge forest and the disappearance of bridges, especially in frontier regions, such as around Charata (Chaco Province). After 2002, connectivity loss was lower than in 2002, but this was likely due to a massive increase in forest patches due to more fragmented patterns in forest conversions than in the previous period, thus generating more stepping stones and hence slightly increasing connectivity at the patch level (Fig. 3).

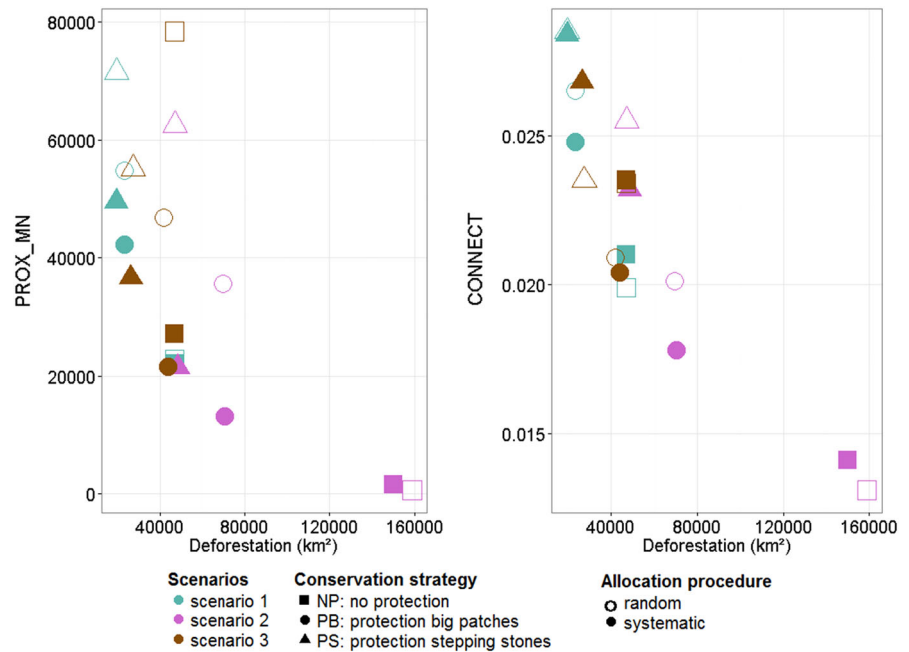
Our analysis of future scenarios reveals that, if all areas where deforestation is possible were converted, only 37 % of the 1977 extent of the Chaco's forest would remain. This percentage is close to thresholds frequently highlighted as critical for species' survival in fragmented landscapes (Fahrig 2003; Camargo

Martensen et al. 2012) and where edge effects could drastically change community structure (de Casenave et al. 1995). Given the increasing demand for food, feed, and biofuel, as well as the strong orientation of Argentine agriculture toward exports, further increases in deforestation are a plausible scenario. Still, our analyses suggest that additional, ecoregional conservation planning could effectively mitigate the outcomes for the region's forests connectivity and biodiversity.

Our fragmentation and connectivity results strongly emphasize the importance of forest patches functioning as stepping stones as key elements for maintaining landscape connectivity (Saura et al. 2013; Villard and Metzger 2014). Stepping stones are particularly crucial in areas where climate change may lead to range shifts of species [Garcia et al. 2014; Gimona et al. (2015)]. Climate change has been marked in the Chaco

**Fig. 6** Connectivity at patch (PROX\_MN) and landscape (CONNECT) levels versus deforestation for each scenario.

Deforestation (in km<sup>2</sup>, x axis) is in logarithmic scale



in the past and is expected to continue to alter vegetation communities (Prado and Gibbs 1993; Bravo et al. 2010; Ferrero et al. 2013; Murgida et al. 2014). Unfortunately, due to their small size and scattered distribution, stepping stones are often disregarded. This also seems to be the case in the Argentine Forest Law, where most stepping stones are assigned to green zones [e.g., remnants of “*bosque de tres quebrachos*” in the southwest of the Chaco province (Torrella et al. 2011)], which would likely lead to their rapid loss without further protection.

Implementing conservation planning that would effectively maintain forest connectivity does not necessarily need to conflict with economic development. For example, our scenarios scenario2\_ps\*, scenario1\_np\* and scenario3\_pb\* resulted in approximate amounts of forest converted to agriculture, but the scenario that would include additional conservation planning to protect some big patches and stepping stones (scenario2\_ps\*), would lead to a substantial reduction in forest connectivity loss (Fig. 6). Thus, low-cost/high-gain situations appear to exist in the Chaco, and smart conservation planning and landscape design (Moilanen et al. 2011; Turner II et al. 2013) that leverages these opportunities are needed to align agricultural production and conservation goals. We thus urge planners involved in the upcoming

revision of the Forest Law to (1) mitigate the inconsistencies of the Forest Law design across provinces, (2) consider forest extent, fragmentation, and connectivity at the ecoregional scale, and (3) incorporate stepping stones as key landscape elements to preserve connectivity.

Ultimately, new protected areas are likely needed to safeguard the Chaco’s forest in the future. Our analysis of conservation priority areas revealed that half of these areas will be lost if the Forest Law is fully implemented. However the preservation of stepping stones would notably enhance the amount of priority areas safeguarded, even under the full implementation of the Forest Law. Currently, Argentina is the Latin American country with the lowest proportion of terrestrial protected areas [1.3 %, Fig. S1, (Elbers 2011)]. A useful approach to identify candidate sites for new protected areas would thus be to supplement the provincial-scale revisions of the Forest Law with an ecoregion-scale assessment of forest fragmentation and connectivity to identify those sites that would retain overall forest connectivity while preserving high-conservation-value areas.

While our sensitivity analyses highlight the robustness of our results, a few sources of uncertainty remain. First, we assumed that agriculture before 1997 only expanded into forested areas, which may be

simplistic for some regions (e.g., Chaco province) where agriculture also expanded into grasslands. Second, we set a MMU of 0.1 km<sup>2</sup>. To check that our choice of MMU did not bias our connectivity analyses, we calculated connectivity indices for a range of MMUs (i.e., 0.05, 0.1 and 0.2 km<sup>2</sup>), showing that our results were robust across MMU scales. Nevertheless, we cannot fully rule out that smaller MMUs may lead to different connectivity results. Third, our connectivity analyses relied on simple, mainly structural indices; however, these have been shown to provide deep insights into regional-scale connectivity, similar to more complex functional connectivity analyses (Doerr et al. 2011; Ernst 2014b; Ziólkowska et al. 2014). We also did not consider matrix quality, which can be important for preserving long-term landscape connectivity (Mastrangelo and Gavin 2014; Ziólkowska et al. 2014). Although desirable, implementing functional and surface-based connectivity measures (such as circuit theory) across our scenarios would be challenging, due to the high number of forest patches and the overall large study area (500,000 km<sup>2</sup>). Fourth, we used a search radius of 2 km for the connectivity and fragmentation analysis, representing maximum movement distances of intermediate dispersers. Sensitivity analyses showed that our results are robust towards the choice of this search radius (Table S2). Although a larger search radius may result in a more connected landscape (and vice versa), this would not affect the relative differences among our scenarios. Fifth, we used generic scenarios that entail simplified descriptions of the future. We consistently used the highest deforestation amount allowed in the provincial forest laws for the sake of comparability among provinces, but lower deforestation amounts may be enforced in some regions (e.g., in Formosa we homogeneously used 60 % of deforestation in green zones when in some regions only 20 % is allowed, Table S1). Although considering socio-economic, demographic, technological, institutional or climate change effects in our scenarios would have been interesting, our goal here was not to identify plausible futures for the Chaco, but to explore the potential effects of the Forest Law under alternative implementations. Sixth, our allocation sampling strategies for potential deforestation (random and systematic) were applied in a mutually exclusive way, while a combination of both processes is likely the most realistic alternative. However, our

results were robust across scenarios and against different allocation procedures (random and systematic), suggesting that our findings are independent from the actual conversion rate or mechanism assumed. Finally, our scenarios dealt with changes in forest only, while other ecosystems are also of high conservation value in the Chaco, such as natural grasslands (Macchi et al. 2013).

Managing for connectivity is challenging for large regions, where planning is often implemented at finer scales and the future effectiveness of conservation planning is uncertain. The implementation of the Forest Law in the Argentine Chaco highlights how sub-regional planning runs the risk of eroding connectivity at ecoregion scales, but also shows that considering overall connectivity can identify low-cost/high-gain options for land-use and conservation planning. Combining connectivity assessments with scenario analyses at scales most relevant for conservation and land-use planning is therefore important for drafting efficient conservation policies that are resilient against future environmental and socioeconomic change—in the Chaco and elsewhere.

**Acknowledgments** We would like to thank R. Grau, I. Gasparri, L. Seghezzo, Y. Le Poulain de Waroux, J. M. Paruelo, and M. Vallejos for valuable discussions and support, and M. Matsumoto (TNC) for sharing their priority areas datasets. We are grateful to C. Israel, C. Levers, F. Gollnow and P. Gärtner for technical support and to A. Gavier for his support in the field. We also thank two anonymous reviewers and the editor M. Bakker for constructive and very helpful comments that improved this manuscript. We gratefully acknowledge funding by the Einstein Foundation Berlin.

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