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Landscape restoration in a mixed agricultural-forest catchment: planning a buffer strip and hedgerow network in a Chilean biodiversity hotspot.

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Abstract Guidance for large-scale restoration of natural or semi-natural linear vegetation elements is often lacking, especially that takes into account the need to maintain human livelihoods such as farming. Focussing on a Chilean biodiversity hostspot, we assessed the landscape in terms of existing woody vegetation elements, proposed a buffer strip and hedgerow network using spatial analysis based on Google Earth® imagery and QGIS, field surveys, seven guidelines linked to prioritization criteria and seedling availability in the region's nurseries, and estimated the budget for implementing the proposed network. The target landscapes require restoring 0.89 ha km^{-2} of woody buffer strips to meet Chilean law; 1.4 ha km^{-2} of new hedgerows are also proposed. The cost of restoration in this landscape is estimated in ca. USD 6,900 planted ha^{-1} of buffer strips and hedgerows. Financial incentives, education, and professional training of farmers are identified as key issues to implement the suggested restoration actions.

Keywords Connectivity; Conservation; Ecosystem services; Farmland; Land-sharing; Living fences

INTRODUCTION

Landscape scale restoration is increasingly advocated to reverse the damage done to biodiversity and human well being by anthropogenic degradation of ecosystems (Rey Benayas and Bullock 2012, Jones et al. 2018). Some recent studies have addressed the topic of large scale restoration planning (Thompson 2011; Morandin and Kremen 2013; Schulz and Schröder 2017); however, further discussion about how to plan such restoration, especially taking into account the need to maintain human livelihoods such as farming, is needed. Agricultural land had spread over ca. 38% of the total global land area by 2014 (FAOSTATS 2017), to the detriment of natural vegetation. Agriculture is the major cause of deforestation (FAO 2016), and the expansion of the agricultural frontier in recently de-forested landscapes such as those found in the South America presents unique challenges to reduce the associated biodiversity loss and environmental degradation. Unfortunately, the largely separate development of production science and conservation biology, which have long focused on providing the knowledge base for intensive food production and biodiversity conservation, respectively, is counterproductive (Brussaard et al. 2010). Landscape-scale ecological restoration in a land-sharing context, which advocates the enhancement of the farmed environment, is a powerful approach to reconcile agricultural production with increased levels of biodiversity and provisioning of a range of ecosystem services (i.e., the benefits that people obtain from ecosystems and, by definition, linked to livelihoods and socioeconomics; MEA 2005), particularly in high-value conservation areas (Rey Benayas and Bullock 2012). Further, it may favour agricultural production itself through ecological intensification processes (e.g. Bommarco et al. 2013).

Buffer strip and hedgerow planting has been highlighted as a relevant land-sharing restoration action (Barral et al. 2015), although a vast majority of studies have been done in Europe. Many studies have shown the positive impact of these natural or semi-natural linear vegetation elements on biodiversity and the delivery of ecosystem services (Dainese et al. 2017; Van Vooren et al. 2017). Specifically, they are beneficial for water regulation (Alegre and Rao 1996), soil maintenance (Lenka et al. 2012), nutrient retention and cycling (Benhamou et al. 2013), pollination (Stanley and Stout 2013), and pest regulation (Wu et al. 2009), which are directly linked to agricultural production. In addition, buffer strips and hedgerows increase biodiversity (Merckx et al. 2012; Dainese et al. 2015), ecological connectivity (Burel and Baudry 2005; Suárez-Esteban et al. 2013) and the aesthetic values of fields and landscapes (Yang et al. 2014), provide a number of products of direct use by humans such as food and wood (Paletto and Chincarini 2012), and may trigger passive revegetation in case of nearby land abandonment by providing seed sources (Forget et al. 2013; Rey Benayas and Bullock 2015). In short, buffer strips and hedgerows can help to produce agroecosystems in which livelihood based upon agricultural production is in partnership rather than in conflict with biodiversity and a wide range of ecosystem services. Their establishment represents a strategy to create high-quality habitats while taking little or no land from crop or pasture production. However, creating these vegetation elements may also lead to risks such as spread of invasive species and diseases and hybridization between cultivated varieties and wild sibling species (Haddad et al. 2014), some of which may in turn affect livelihoods.

In the context of societal demand for sustainable agriculture (Fischer et al. 2017) and regional and global forest restoration and climate mitigation targets (e.g. the 2011 Bonn Challenge, the 2014 New York Declaration, and the 2016 20x20 Initiative), buffer strip and hedgerow restoration in agricultural or mixed agricultural-forest landscapes should be broadly implemented (Rey Benayas and Bullock 2015). Previous work has pointed out the necessity of conserving and restoring buffer strips and hedgerows (Dainese et al. 2017) to e.g. increase landscape connectivity (Albert et al. 2017; Isaac et al. 2018) and other services (see references above). However, as far as we know, there is not any study that has actually planned their restoration in a scientifically informed and quantitative manner at the catchment scale, and estimates the necessary budget to meet such a goal (although there have been attempts at smaller scales, e.g. Groot et al. 2010).

In this study, we plan a buffer strip and hedgerow network to reconcile agricultural production, biodiversity, and provisioning of ecosystem services at the field and landscape scale. This is as a preliminary step for cost-effective implementation of restoration. Our proposed restoration plan is illustrated in a catchment of the Central Valley in the Araucanía region, South-Central Chile (**Figure 1**). The Araucanía is located in the Valdivian Rainforest Ecoregion (35°S - 43°30' S), which is recognized as a global biodiversity hotspot (Myers et al. 2000). Native forests covered ca. 11.3 million ha in this Ecoregion at the time of the Spanish conquest, but their conversion to chiefly agricultural land and exotic tree plantations has reduced the extent by 46.6% (Lara et al. 2012). Today, most land cover (ca. 75%) in the Araucanía Central Valley is cropland and pasture land, with a recent increase in exotic tree plantations (ca. 11%; Miranda et al. 2015).

To accomplish our objective, we first present some general guidelines for buffer strip and hedgerow restoration in a land-sharing context. The guidelines as a whole are designed to maximize a range of ecosystem services by taking advantage of the linear elements in the landscape in a realistic way. We then tailor these guidelines to our case study using a four-level approach: the catchment, representative agricultural landscapes, individual agricultural fields, and field plots. For this, we: (1) assess the landscape in terms of the existing woody vegetation elements, namely buffer strips, hedgerows, tree lines, native forest remnants, and exotic tree plantations; (2) propose a buffer strip and hedgerow network considering landscape spatial analysis, field surveys, prioritization criteria, and seedling availability in the region's nurseries; and (3) estimate the budget for implementing the proposed network. Our case study illustrates how to tackle a complex issue in the "real world", where agriculture and forest restoration usually compete for land use, and may inspire similar approaches in other regions. Results from this study, which is focussed on practice and with explicit management recommendations and cost estimations, will be particularly useful to farmers, land owners, practitioners, and land use planners.

GUIDELINES FOR BUFFER STRIP AND HEDGEROW RESTORATION

The general guidelines for buffer strip and hedgerow restoration that are proposed here are inspired by the scientific evidence for expected benefits on biodiversity and ecosystem services (e.g. Van Vooren et al. 2017). They stem from legal requirements (guideline (1) below), our 10-year experience as practitioners related to the Field for Life project of the International Foundation for Ecosystem Restoration, which so far has been implemented in Europe (guidelines (2) and (3); Rey Benayas and Bullock 2015; Rey Benayas et al. 2016), and ecological principles such as connectivity, interception of water flow, dispersal, and niche complementarity (guidelines (4) to (7)). These will be illustrated for three 3x3-km representative agricultural landscapes in our study area.

These guidelines are designed to comply with legal constraints and to maximize a broad range of ecosystem services such as habitat provision and connectivity, runoff regulation, and nutrient and sediment retention. Guideline (1), which is related to buffer strip restoration, is mandatory by law, and guidelines (2) and (3), which are related to hedgerows, propose targets in terms of the field area to be restored. Guidelines (4) and (5) refer to prioritization criteria for hedgerow restoration related to connectivity of existing forest remnants and interception of water flows, respectively. Together, guidelines (2) to (5) will result in priority hedgerows for either connectivity or water flow interception and non-priority hedgerows. Guideline (6), which is related to both buffer strips and hedgerows, prioritizes planting based on the potential of natural regeneration of these linear vegetation elements. Finally, guideline (7) is related to the species composition of the plantings. The guidelines comprise:

(1) Restore the woody vegetation of buffer strips along both sides of all water courses according to the relevant laws, regulations and jurisdictions. In our case study, this means creating 10-m or 20-m wide woody buffer strips (for slopes ≤ or >45º, respectively) along both sides of all water courses (see Romero et al. 2014 for an analysis of the legal context for riparian areas in Chile).

(2) Restore hedgerows (where they are lacking) on all boundaries of fields > 2 ha, provided that field boundaries are not adjacent to buffer strips or native forest remnants (note that hedgerow prioritization is addressed in guidelines (4) and (5), and type of restoration in guideline (6)). The rationale for this proposed minimum field area, which also applies to the next guideline and is supported by our experience as practitioners, is not to alienate land owners due to perceived negative financial effects.

This area is close to the mean area of the smallest fields in our case study (namely 2.47 ± 2.23 ha, **Table S1**).

(3) Ensure hedgerow widths sufficient to comprise 5% by area of a target field. This figure is less than others reported in the scientific literature (e.g. 6% of Lutz and Bastian 2002). If the target field already had 5% of existing native woody vegetation elements, the width of hedgerows to be planted is to be a maximum of 5 m.

(4) Prioritize those field boundaries or buffer strips that connect native forest remnants of ≥ 0.5 ha – this threshold area fits the "forest" definition of FAO 2000- under the least-cost path criterion (Gurrutxaga et al. 2010).

(5) Prioritize those field boundaries that are perpendicular to the slope. This would maximize benefits related to runoff and water retention, including the reduction of soil erosion and diffuse pollution, and enhancement of nutrient retention (e.g. Maringanti et al. 2009).

(6) Prioritize active restoration (i.e. planting) on sites at relatively long distances (> 50 m in our case study) from existing buffer strips, hedgerows, or native forest remnants. The sites located at relatively short distances from these seed sources are proposed to be left for passive restoration (i.e. natural regeneration) to reduce costs (Rey Benayas et al. 2008; Forget et al. 2013).

In this study, planning of guidelines (1) to (6) is based on Google Earth® imagery analysis (see below); this imagery is quite easy to acquire. Alternatively, for landscape planning, other types of images (commercial flights, drones, etc.) could be used provided they have an adequate spatial resolution. For local planning, e.g. a field or group of close fields, *in situ* visual inspection would be sufficient to use these guidelines.

(7) As for the species composition of the plantings, we propose: (a) use as reference the buffer strips deemed of good ecological condition (Forget et al. 2013) and the edges of native forest remnants; (b) plant only native species (e.g. Correll 2005); (c) favour those species with high Importance Value Index in the reference vegetation (Gatica-Saavedra et al. 2017); (d) plant a range of species, i.e. species rich plantings, to allow environmental sorting of those best suited to the local conditions (Rey Benayas et al. 2016); (e) plant species with complementary functional traits (e.g. life form and deciduousness) to enhance niche partitioning and resource acquisition (Hallet et al. 2017); and (f) plant a high density to speed up vegetation development (Rey Benayas et al. 2016). In our case study, the planting modules –i.e. units to be replicated- were designed on the basis of the species composition at surveyed reference plant communities in field plots (see below) and seedling availability of native species in four nurseries within the study area (**Table S2**). However, we point out that fine-scale species plot data are not always available and may be expensive and/or time consuming to get. In these cases, to select species for plantings, more simple approaches and resources, which are often available on-line, such as species distribution maps, general vegetation descriptions, or consultation with local or regional experts –including the nursey managers- should be considered (e.g. Rey Benayas et al. 2016).

Despite being desirable, we do not propose here the replacement of exotic species with native species as this task is not feasible for its cost at present at our scale of work.

METHODS

Study area

We studied a 2303-km^2 catchment located in the Chilean Central Valley (mid coordinates are 38º 51' S latitude, 72º 20' W longitude; **Figure 1**). The climate is temperate, with a mean annual temperature of 12 ºC and a total annual precipitation of 1191 mm. Elevation range is 50-2887 m asl. However, agricultural land ranges between 50 and 700 m asl; ca. 20% of the western part of the catchment, above 700 m, is mostly covered by native forest, shrubland and exotic tree plantations or is unvegetated at the highest elevations. Soil types are andisols and inceptisols. Major land use/cover types in 2013 were pasture land (40%), native forest or exotic tree plantation (38%), cropland (13%), and shrubland (7%) (inferred from Zhao et al. 2016). In the period 1973-2008, major land cover changes were an increase in agricultural land (+4230 ha) and tree plantations (+15 620 ha) and a decrease in native forests (-28 170 ha) (Miranda et al. 2015). In brief, the major arguments that justify a large scale restoration program of buffer strips and hedgerows in this study area are its status as a global biodiversity hotspot with high rates of conversion of native forests to exotic tree plantations and the expansion of the agricultural frontier, and the benefits to biodiversity conservation and delivery of ecosystems services which might be gained by restoration.

Characterization of agricultural landscapes

We characterized representative agricultural landscapes in this area using open source platforms including Google Earth® imagery taken in 2016, Google Earth Pro® (2015) for manual delineation and digitization, and QGIS software (2004-2016) for measurements (see **Figure S1** for a graphical summary of the methodology implemented in this study). This characterization is the basis, in practice, for the implementation of the proposed guidelines (1) to (6) explained above.

We first used the official Chilean *Dirección General de Aguas* (2010) drainage network layer, which was geographically corrected prior to digitization, to identify all water courses in the catchment. We measured the length and the width of existing buffer strips, distinguishing woody vs. herbaceous buffer strips, at 500 points randomly distributed along the water courses and in 20 randomly selected agricultural fields across the catchment (see **Appendix S1** for more details).

The visual inspection of Google Earth® imagery that covered the catchment allowed us to distinguish three major types of agricultural landscapes (**Figure 1**) that noticeably differed in their field size and presence of woody vegetation elements, namely the Large, Small and Heterogeneous field types (**Table S1, Figure S2A-C**). To characterize these agricultural landscape types, we selected a total of 80 individual fields in the catchment that were digitized. Of those 80 fields, 20 were randomly distributed throughout the entire catchment. We next selected three 5x5-km representative agricultural landscapes of these field types and each received 20 random samples (i.e., individual fields) as well.

Each 5x5-km representative agricultural landscape was characterized in terms of buffer strips, hedgerows, tree lines, native forest remnants, and exotic tree plantations. We measured the following features for each agricultural field: (1) buffer strip, (2) hedgerow and (3) tree line length, (4) buffer strip and (5) hedgerow width, (6) no. of forest remnants within and adjacent to the fields, (7) forest remnant area within the field, (8) forest remnant edge to the field, (9) no. of exotic tree plantations within and adjacent to the fields, (10) tree plantation area within the fields, (11) tree plantation edge to the field, and (12) no. of isolated tress. Shrub cover is virtually non-existent in the study area, and there is a hard contact between forest fragments or tree plantations and cropped or pasture fields. Further details on characterization of agricultural landscapes types are provided in **Appendix S1.**

Delineation of the proposed restoration network

The proposed buffer strip and hedgerow restoration network was illustrated for 3x3-km areas centered in the 5x5-km representative agricultural landscapes to make the resulting figures more clear. It was also based on visual inspection of Google Earth® imagery, Google Earth Pro® (2015) for manual delineation and digitization and QGIS software (2004-2016) for measurements. To plan the buffer strip network in these areas, we first delineated and digitized those water course edges where woody buffer strips should be restored to meet legal requirements (Guideline no. 1). As a prior step for this delineation, the width of existing buffer strips was measured at three random points per target field and then averaged. These three random points are a subset of the ten random points used to characterize the landscapes (**Appendix S1**).

To plan the hedgerow network, we first excluded those fields < 2 ha (Guideline no. 2). As Guideline no. 3 requires a hedgerow width sufficient to comprise 5% by area of a target field, the width of existing hedgerows was also measured at the same three random points per target field that were used for buffer strips and then averaged, and the width of the borders of native forest remnants and tree plantations in the fields was considered as being 10-m wide.

Guidelines no. 4, 5 and 6 prioritize hedgerow restoration. Planning of Guideline no. 4, which prioritizes hedgerows that connect forest remnants ≥ 0.5 ha, was based on the measures of remnant forest area. For planning Guideline no. 5, which prioritizes hedgerows that intercept flows, we used the Google Earth tool “Elevation profile” to identify the field boundaries that are most perpendicular to the slope, typically one or two boundaries per target field, among all field boundaries. This task was done with the aid of a digital elevation model that visually suggested the slope direction and manually testing one or two elevation profiles per boundary of each target field in the landscape. In practical terms, this task is repeatable due to the relatively flat agricultural landscapes and regular shapes of the fields. Planning of Guideline no. 6, which distinguishes planting sites at > 50 m from existing buffer strips, hedgerows, or native forest remnants from closer sites that are proposed for natural regeneration, was based on the measured closest distances of field boundaries to existing buffer strips, hedgerows, or native forest remnants.

Plant community composition

We surveyed the plant community composition of the five vegetation elements mentioned above to inform the proposed plantings in the target agroecosystems (**Figure S1**), i.e. the basis for the implementation of guideline (7). The survey was conducted at 45 individual fields (15 per 5x5-km representative agricultural landscape). At each field, one 20x3-m plot was randomly placed at each occurring woody vegetation element. The number of plots per field ranged between 1 and 4 (mean ± sd = 2.2 ± 0.9; mode = 3 plots). One side of the plot always coincided with the crop-edge. We surveyed a total of 102 20x3-m plots for occurrence, number of individuals, dbh, and height of all shrubs and trees with dbh ≥ 5 cm or height ≥ 1.3 m. The plots were located on hedgerows (31 plots), buffer strips (28, of which 5 were deemed of good ecological condition and 23 were of degraded condition, see Results), tree lines (16), edges of native forest remnants (17), and edges of tree plantations (10).

We calculated mean species richness and number of individuals per plot and the Importance Value Index (IVI, which is based on species relative density –i.e. number of individuals-, relative frequency –i.e. number of plots where it occurred- and relative basal area across plots) of the surveyed shrub and tree species for all 102 sampled plots and for the plots surveyed in each of the various woody vegetation elements. The good ecological condition buffer strips and edges of native forest remnants plots were used as reference plant communities to design the planting modules. We also took advantage of six 500x2-m transects located in five native forest remnants > 2 ha and one 87-m wide good condition buffer strip that were surveyed as part of another project (**Appendix S1; Table S5**). A Non-Metric Multidimensional Scaling (NMDS, Legendre and Legendre 1993) that allowed us to explore visually plant community composition of the vegetation elements was used to assist the design of the planting modules (**Appendix S1**; **Figure S3**).

Budget estimation

Finally, we estimated the budget necessary to accomplish the proposed buffer strip and hedgerow network for the three 3x3-km areas centered at the 5x5-km representative agricultural landscapes, i.e. the same operational scale than for delineation of the proposed restoration network. The major components of the budget were (1) the cost of seedlings to be planted that would be acquired from four nurseries within the study area and (2) the operational costs of planting. We estimated our budget with the cheapest available 1-yr old seedlings in all four nurseries (**Table S2**). The operational costs of planting per seedling according to two local practitioners, including seedling transportation to planting sites (USD 1.58-2.4 km^{-1}, USD 0.02-0.022 per seedling), plant protectors (USD 0.24-0.27), and labor (USD 0.26-0.44) was estimated in USD 0.52-0.73 (**Table S6**). We did not consider the replanting related costs because our plantation density was higher than that found in our field surveys (see below), thus allowing for seedling mortality. Consequently, we did not consider the post-operational costs of monitoring the establishment of planted seedlings for the same reason that we did not do so for the replanting costs and because these monitoring costs would be marginal compared to the seedling and operational costs.

RESULTS

Characterization of agricultural landscapes

At the catchment level, our spatial analysis revealed 1597.6 km of rivers and streams and a total of 2119.6 ha of woody buffer strips, i.e. 0.9% of its area. Forty-four of our 500 measured random points fell into fully forested catchments and hence cannot be properly called buffer strips. Measures from the remaining 456 points gave a total length of 226.3 km (496.2 m ± 28.9 SD per point) and an average width of 119.5 m ± 326 SD of existing buffer strips, of which 207.8 km (455.7 m ± 98.5 SD per point) of 102.6 m ± 325.7 SD width were woody vegetation and the rest were herbaceous vegetation. Interestingly, in the three selected 5x5-km representative agricultural landscapes, buffer strips by the water courses usually remained.

Overall, in the 20 randomly selected agricultural fields across the catchment, buffer strips and hedgerows accounted for a total of 100.8 and 413 km, 5.1 and 20.9 m ha^{-1}, and 4.6 (1.84%) and 6.9 (2.75%) ha, respectively. The forest remnants, tree plantations, and tree lines provided 403.8 (20.4 m ha^{-1}), 121.15 m (6.1 m ha^{-1}), and 105 m (5.31 m ha^{-1}) respectively, of woody edges to the fields (**Table S1D)**. The length of hedgerows, tree lines, native forests, and exotic tree plantations varied largely among the three representative agricultural landscapes (**Table S1, Figure S2A-C)**. More details on results of landscape characterization are provided in **Appendix S2**.

Proposed buffer strip and hedgerow restoration

At the catchment level, our analysis based on the delineation, digitization and measurement of length and width of existing buffer strips at 456 points randomly distributed along the water courses, suggests that 18.5 km (40.5 m ± 94 SD per sampled point) of herbaceous buffer strips, with an average width of 6.9 m ± 21 SD, should be restored. We identified 65 sampling points that did not meet the Chilean law of occurrence of woody buffer strips, which represented 41.5 ha in total. Extrapolation of these calculations resulted in a total of 2040 ha (0.89 ha per catchment km^2) of buffer strips to be restored in the catchment to meet legal requirements (i.e. Guideline 1).

To illustrate our proposed restoration scheme, we produced a map and a set of figures for each of the 3x3-km representative agricultural landscapes (**Figures 2-4**). These maps result from the overlap between existing woody vegetation elements and the guidelines explained above (**Figure S1**). The length and area of buffer strips and hedgerows to be restored for the three agricultural landscapes are summarized in **Table 1,** which reports prioritization scenarios based on guidelines 4 to 6. Guidelines 4 and 5, which are related to hedgerow restoration only, distinguished "priority" hedgerows that connect forest remnants ≥ 0.5 ha or these and buffer strips, or that are perpendicular to slope (**Table 1 b1 and c1**), from "non-priority" hedgerows (**Table 1 b2 and c2**). Guideline 6 distinguished active restoration (planting) of both buffer strips and hedgerows on sites located at distances > 50 m from existing buffer strips, hedgerows, or native forest remnants from passive restoration (natural regeneration) sites (**Table 1 b-c**).

We found only five fields out of 192 fields adjacent to water courses in the three 3x3-km landscapes that did not meet the Chilean law of buffer strip width, so the resulting length and area of buffer strips to be restored is rather small and actually 0 in two of the three landscapes (**Table 1a**). We also found that a relatively low proportion of fields (31.3% in the Large field agricultural landscape, 14.5% in the Small field one, and 24.4% in the Heterogeneous field type) did not meet our criterion of 5% area of existing native woody vegetation elements (Guideline 2).

Proposed planting modules

For plantings at the active restoration sites, we propose four 20x3-m planting modules, one for buffer strips and three for hedgerows (**Table 2**). We designed just one module for buffer strips because the area to be planted was very small (see above). These modules, overall, aim to satisfy the criteria of Guideline 7 and were designed, first, on the basis of composition (**Table S4; Figure S3**), native character (**Table S4**), importance value (**Table S4**), species richness (**Table S3**), complementarity of functional traits (**Table S2**), and density (**Table S3**) of the surveyed reference plant communities. A secondary consideration was the availability of the target species at the nurseries (**Table S2**).

Our survey of woody plant community composition resulted in a list of 33 shrub and tree species, of which 20 were native. Reference buffer strips were dominated by *Nothofagus obliqua*, *Drimys winteri* and *Aristotelia chilensis*. Hedgerows and edges of native forest remnants were dominated by *N. obliqua, Laurelia sempervirens,* and *A. chilensis*. Nine native species occurring at edges of native forest remnants –principally *Lomatia dentata* and *D. winteri* - did not occur at the hedgerows (**Table S4**). All but one (*Rhaphithamnus spinosus*) of the eight most important native species were available at the local nurseries. To better fulfil the criteria "species rich plantings" and "plant species with complementary functional traits", we used five additional species of lesser importance in the surveyed reference sites that were available at the nurseries (**Table 2** and **Table S2**).

Species richness and the total number of seedlings for designed modules are the double of their values at the field survey plots for reference plant communities (**Table 2**). Similarly, each module includes a number of seedlings for each species proportional to their IVI in reference plant communities except for the species subordinated to *N. obliqua* at the edges of native forest remnants, which was highly dominant at these sites (**Table S4**). More information on plant community composition of all surveyed landscape elements, particularly of degraded buffer strips, existing hedgerows, and tree lines can be found in the Supplementary material (**Appendix S2**).

Estimated budget

The average estimated cost of buffer strip plantings was USD 7396 ha^{-1} (**Table S6**). The estimated budget to restore buffer strips was USD 740 (82.2 km^{-2}) for the Heterogeneous field landscape, the only assessed landscape that required planting (**Table 1 a2**). The budget for planting all buffer strips in the catchment to meet Chilean legal requirements was estimated in USD 15.1 million. If passive restoration is allowed and based on the relative proportions of proposed passive restoration vs. plantings (**Table 1a2**), the investment would mostly be necessary in heterogeneous field landscapes only (see location on **Figure 1**) and reduced by one third. However, this strategy would require the exclusion of cattle resulting in opportunity costs or fencing costs.

The average estimated cost of hedgerow plantings ranged between USD 6619 and USD 7169 ha^{-1} (**Table S6**). The estimated budget to accomplish the proposed hedgerow network in the representative 3x3-km^2 agricultural landscapes –assuming an average cost of USD 6894 ha^{-1} (**Table S6**)- ranged between USD 14 477 (1609 km^{-2}) for the priority scenario in the Small-field landscape (**Table 1 c1**) and USD 111 683 (12 409 km^{-2}) for all plantings in the Large-field landscape (**Table 1 C**).

DISCUSSION

Feasibility of the proposed restoration scheme

Reconciling ecological restoration and agricultural production is acknowledged as a critical but elusive goal (Cabin et al. 2010). In this paper we have developed a restoration scheme for buffer strips and hedgerows at the landscape scale, a land-sharing restoration approach that allows farmland production and biodiversity and linked ecosystem services because these linear natural and semi-natural vegetation elements compete very little with agricultural land use (Rey Benayas and Bullock 2012). Accordingly, the Central Valley of the Araucanía, where our study catchment is located, offers opportunities for mosaic forest restoration but not for large scale forest restoration (WRI 2017). Quantifying biodiversity, ecosystem services and other socioeconomic outcomes is essential for understanding the full benefits and costs of ecological restoration and to support its use in natural resource management (Wortley et al. 2013). Similarly, as introduced earlier, the potential ecological costs ("dis-services") and economic costs other than those of the restoration actions themselves must be considered as well. However, these tasks are beyond the objectives of this study as we focused on guidelines, implementation plan, and estimated budget of an operational restoration project.

A key issue for large-scale ecological restoration on agricultural land is financial support (Rey Benayas and Bullock 2015) and, although there is growing evidence that restoring agricultural land can have positive impacts on biodiversity and delivery of ecosystem services, how to finance these actions remains a big challenge. The average financial turnover of farms in the study region is highly variable, but some illustrative figures are 300-400 USD ha^{-1} yr^{-1} for the major crops, namely wheat and rapeseed (ODEPA 2018), and pastures. We estimated the direct cost of plantings to be ca. USD 6900 ha^{-1}, and a small opportunity cost related to loss of crop or pasture production due to the proposed restoration actions should be considered as well (but see Van Vooren et al. 2017, figures below). Who pays this bill? In practice land, owners must be specifically supported or rewarded for restoration actions on their properties. The financial benefits that might eventually comprise are actually a reward to land owners.

Some studies have shown these benefits (e.g. Lenka et al. 2012), but others have failed to do so (e.g. Alegre and Rao 1996). According to Van Vooren et al. (2017), in temperate areas, within a distance of twice the hedgerow height, arable crop yield is reduced by 29%, whereas beyond this distance, to 20 times the hedgerow height, crop yield is increased by 6%. Pywell et al. (2015) showed that planting wildflower buffer strips in similar fields led to an enhancement of crop yield which compensated for the conversion of cropland to wildlife habitat. We suggest that a certified, sustainable wood extraction from buffer strips and hedgerows may partially compensate land owners as firewood is the major fuel in the study region for heating. In any case, these financial benefits may be insufficient. Tax deductions for land owners who restore agricultural land and donations to not-for-profit organizations that run restoration projects, payment for environmental services (PES), and direct financing measures related to restoration activities should be implemented (Rey Benayas and Bullock 2015). However, incentives related to tax deduction and PES are non-existent in Chile today. There are though a number of nurseries and forest companies in the region that will obviously benefit from such restoration actions, which will create a number of jobs as well. This study supports recommendations for planning seedling production in the nurseries, particularly of those native species that are not produced at present.

Guidelines and prioritization criteria

Our proposed restoration scheme followed a range of guidelines and prioritization criteria, some of which may be considered as arbitrary (particularly for hedgerows). The completion of 10-m or 20-m width buffer strips along both sides of all water courses to meet the Chilean law (Romero et al. 2014), irrespective of the area of affected fields, is though an “objective” criterion, but we foresee that it may be difficult to accomplish in the case of small fields.

We set up the goal of planting hedgerows in all fields ≥ 2 ha. However, as explained above, most of these fields maintain hedgerows and it is the replacement of woody exotics by native species rather than the completion of their hedgerow network the actual challenge (details on exotic species are provided in **Appendix S2** and **Table S4**). We also propose a hedgerow width sufficient to complete 5% of the field area to avoid a negative response by land owners. Comparably, Lutz and Bastian (2002) calculated that 6% of the agricultural area could be withdrawn from cultivation without any negative financial effect for the farmers in Saxony (Germany), Pywell et al. (2015) showed wildflower buffer strips comprising 3-8% of field areas were cost-neutral because of the enhanced crop yields, Moreno-Mateos et al. (2010) suggested the conversion to wetland of 1.5-4% of an intensively irrigated Mediterranean catchment for optimum nutrient retention, and the Swiss standards for organic farming certification requests 7% of ecological compensation areas with natural or semi-natural vegetation (Aviron et al. 2009). The prioritization of field boundaries that connect forest remnants ≥ 0.5 ha or these remnants with existing buffer strips and that are perpendicular to the slope is grounded in scientific theory and multiple studies (e.g. Rao et al. 2009). We propose to leave to passive restoration those sites located at distances < 50 m from existing buffer strips, hedgerows, or native forest remnants that may act as seed sources. Various studies have shown that landscape structure is a major factor for recolonization: the more the target boundary is surrounded by buffer strips and hedgerows, the more the recolonization by trees is effective, but outcomes may be strongly context dependent (Crouzielles et al. 2016). Finally, as for the species composition of the plantings (Guideline 7), we propose six rules grounded on well established principles of ecological theory, biological conservation and ecological restoration. We acknowledge, though, that the implementation of these rules may be context dependent, particularly in relation to the specific objectives of the restoration project (for instance, McGonigle et al. 2016 developed a tool to select a subset of potential plant species with different flowering times and pollinator preferences).

Part of our methodological approach was based upon manual digitization and delineation using Google Earth® imagery and Google Earth Pro® (2015) tools, and measurements of target landscape elements using QGIS (2004-2016). There are pros and cons in using these methods. Positively, these are open platforms, hence accessible to anybody and, in part (e.g. visual inspection of and simple measures on Google Earth® imagery), do not require specialized training, so a wide range of practitioners and even land owners may use them. The spatial resolution of the imagery allowed accurate estimation at the field level, which is the operational unit of the restoration work. Our approach may therefore be considered a step forward in providing tools for buffer strip and hedgerow restoration planning. However, these methods are time consuming, and the invested time would have been highly reduced if there had been existing material of high quality (e.g. accurate information layers of field boundaries). We note as well that the figures given for buffer strip and hedgerow restoration effort and its costs at the landscape scale are approximations based on visual interpretations and extrapolations with limitations in terms of accuracy.

Characteristics of farmed fields

We ultimately attribute the types of agricultural landscapes we distinguished to differences in land tenancy and use intensity. Agricultural production in larger fields is more intensive and land concentration and mechanization has favoured the extirpation of buffer strips and hedgerows (Burel and Braudy 2005). These fields conserve however a relatively high number of isolated trees that provides shelter for the domestic livestock and have some native forest remnants, thus providing opportunities for enhancing connectivity (Prevedello et al. 2018). On the other side, most of the smallest fields, which are owned by indigenous Mapuche people, maintain hedgerows mostly due to little mechanization and the benefit of property separation. A considerable amount of these hedgerows and all tree lines are dominated by exotic woody plants, as other studies have shown (Wilkerson 2014), and their replacement by native woody plants is challenging (Correll 2005; Hallet et al. 2017). Due to the lack of appropriate financial incentives in the area, our results suggest to actively restore only homogenous landscapes as restoration actions in heterogeneous, "complex" landscapes, which already support relatively high levels of biodiversity and ecosystem services, would result in less recognizable benefits.

The occurrence, length, and width of buffer strips and hedgerows are highly variable across agricultural landscapes (e.g. Gelling et al. 2007; Davies and Pullin 2007). For instance, in a Costa Rican agricultural landscape, live fences accounted for 45.4% of all fences in the landscape, occurred with a mean density of 50.5 m ha^{-1} and covered < 2% of the total area of the landscape (León and Harvey 2006). The simulations ran by these authors showed that the conversion of all existing wooden fences to live fences would greatly enhance landscape connectivity by more than doubling the area, density and number of direct connections to forest habitats, and reducing the average distance between tree canopies.

CONCLUSIONS

As rural landscapes must shift from an almost unique function of agricultural production toward a multifunction of biodiversity conservation, environmental protection, amenity and production, the conservation and restoration of buffer strip and hedgerow networks becomes of greater importance (Burel and Braudy 1995). We provided a plan for such restoration that takes into account the maintenance of farming, which is a major human livelihood in the target landscape. However, as practitioners, we have learnt that, in the first instance, farmers are usually reluctant to implement the suggested restoration projects for three major reasons (Rey Benayas and Bullock 2015). First, farmers do not usually understand or foresee the benefits for agricultural production and, simultaneously, they perceive risks for agricultural production. The second one has to do with their aesthetic appraisal of crop fields. According to their perception, crop fields must be “clean”, i.e. with nothing other than the cultivated plants, and often farmers that have “untidy” crop fields are criticized in their local communities. And third, generally, individual farmers react to the private use-value of biodiversity and ecosystem services assigned in the marketplace and thus typically ignore the ‘external’ benefits of conservation that accrue to wider society (Jackson et al. 2007). To overcome this reluctance, we recommend efforts to educate and show farmers that buffer strip and hedgerow restoration enhances the environment and, importantly, may enhance crop production (Rey Benayas and Bullock 2015; Dainese et al. 2017). Thus, another key challenge for implementation of these plans is to demonstrate that the proposed restoration practices benefit not only the environment but also crop production (Pywell et al. 2015). Actually, this may be often the unique argument to convince farmers for restoration actions and, in the meantime, financial incentives must be implemented. Professional training is necessary as well to build up the capabilities to enterprise the proposed restoration actions (e.g. McCracken et al. 2016). To make this happen, the International Foundation for Ecosystem Restoration and the University of La Frontera have initiated a demonstration project at the Maquehue state, in the study area, with the hope of catalyzing institutional and societal cooperation for these efforts.

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Table 1. Summary metrics of the proposed restoration scheme to complete the buffer strip (a) and hedgerow network (b, c) at three 3x3-km representative agricultural landscapes in the catchment (**figures 2-4**). The figure numbers distinguish goals for passive restoration and for plantings and, in the case of hedgerows, priority and non-priority targets.

	Large field landscape	Small field landscape	Heterogeneous field landscape
(a1) Buffer strip length (m) (Passive/Plantings)	NA	NA	749.8 482.0/ 267.8
(a2) Buffer strip area (ha) (Passive/Plantings)	NA	NA	0.4 0.3/ 0.1
(b) Hedgerow length (m) (Passive/Plantings)	26496.2 3561.3/ 22934.9	9865.0 714.2/ 9150.7	21204.2 5390.4/ 15813.8
(b1) Priority restoration (m) (Passive/Plantings)	11873.7 1338.2/ 10535.5	4293.0 307.5/ 3985.4	9398.5 3880.5/ 5518.0
(b2) Non-priority restoration (m) (Passive/Plantings)	14622.5 2223.0/ 12399.4	5572.0 406.7/ 5165.3	11805.7 1509.9/ 10295.8
(c) Hedgerow area (ha) (Passive/Plantings)	18.3 2.1/16.2	5.3 0.4/ 4.9	15.3 3.4/ 11.9
(c1) Priority restoration (ha) (Passive/Plantings)	8.3 0.8/ 7.5	2.3 0.2/ 2.1	6.4 2.5/ 3.9
(c2) Non-priority restoration (ha) (Passive/Plantings)	10.1 1.4/ 8.7	3.0 0.2/ 2.8	8.9 1.0/ 7.9

Table 2. Proposed planting modules to restore buffer strips and hedgerows in the Araucanía. The numbers in the cells represent the number of individuals for each species at each module of 20x3-m. Complementary information related to the characteristics of shrub (S) or tree (T), evergreen (E) or deciduous (D), successional stage (E: Early, I: Intermediate, L: Late) and phenology of flowering and fruting (A: Autumn, Sp: Spring, Su: Summer, W: Winter) is reported for each species.

Species	Module 1 (Buffer strips)	Module 2 (Hedgerow)	Module 3 (Hedgerow)	Module 4 (Hedgerow)
Nothofagus obliqua T, D, E, Sp, Su	5	8	8	8
Drimys winteri T, E, E, Sp, Su	3		3	
Laurelia sempervirens T, E, I, Sp, Su	1	3		
Aristotelia chilensis T, E, E, Sp-Su, Su	2	2		
Persea lingue T, E, I, Sp, Su-A	2		2	
Maytenus boaria T, E, E, Sp, Su	2			
Lomatia dentata T, E, I, Sp, Su		2		
Aextoxicon punctatum *T, E, L, Sp, Su-A*			2	
Buddleja globosa	1			

S, E, E, Sp, A				
Eucryphia cordifolia *T, E, L, Su, A*				3
Myrceugenia exsucca *T, E, L, Su, W*				2
Nothofagus dombeyi *T, E, E, Sp, S*				2

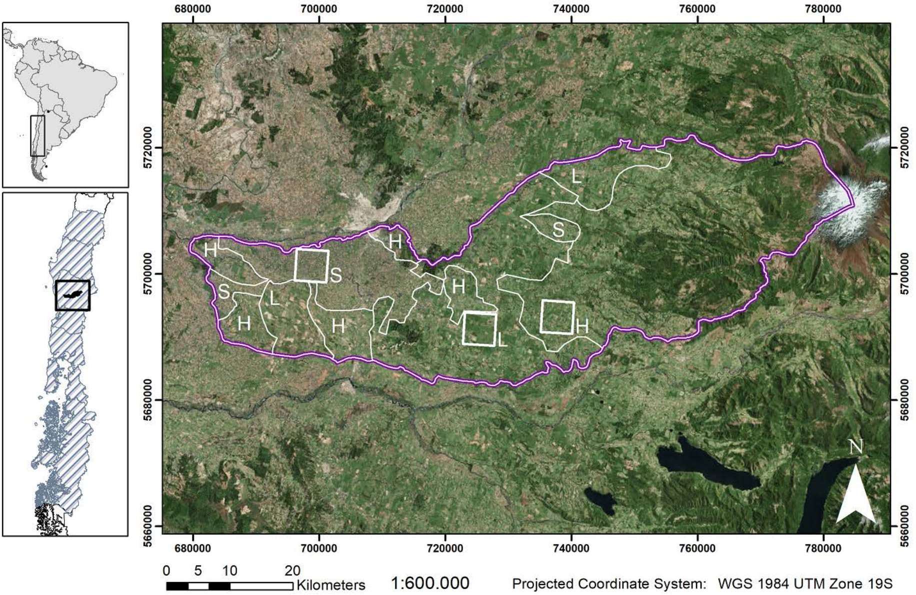
Figure legends

Figure 1. Location of the study catchment in the context of South America, Central Valley of Chile and the Valdivian Rainforest Ecoregion, showing the three 5x5-km representative agricultural landscapes that were analyzed in detail. The polygons represent major types of agricultural landscapes with contrasting field features, namely L = large fields, S = small fields, and H = heterogeneous and intermediate fields. The images corresponding to the individual 5x5-km agricultural landscapes are shown in **Figure S2**.

Figure 2. Proposed restoration scheme of the buffer strip and hedgerow network in the 3x3-km agricultural landscape that is representative of fields of heterogeneous size.

Figure 3. Proposed restoration scheme of the hedgerow and buffer strip network in the 3x3-km agricultural landscape that is representative of small fields.

Figure 4. Proposed restoration scheme of the hedgerow and buffer strip network in the 3x3-km agricultural landscape that is representative of large fields.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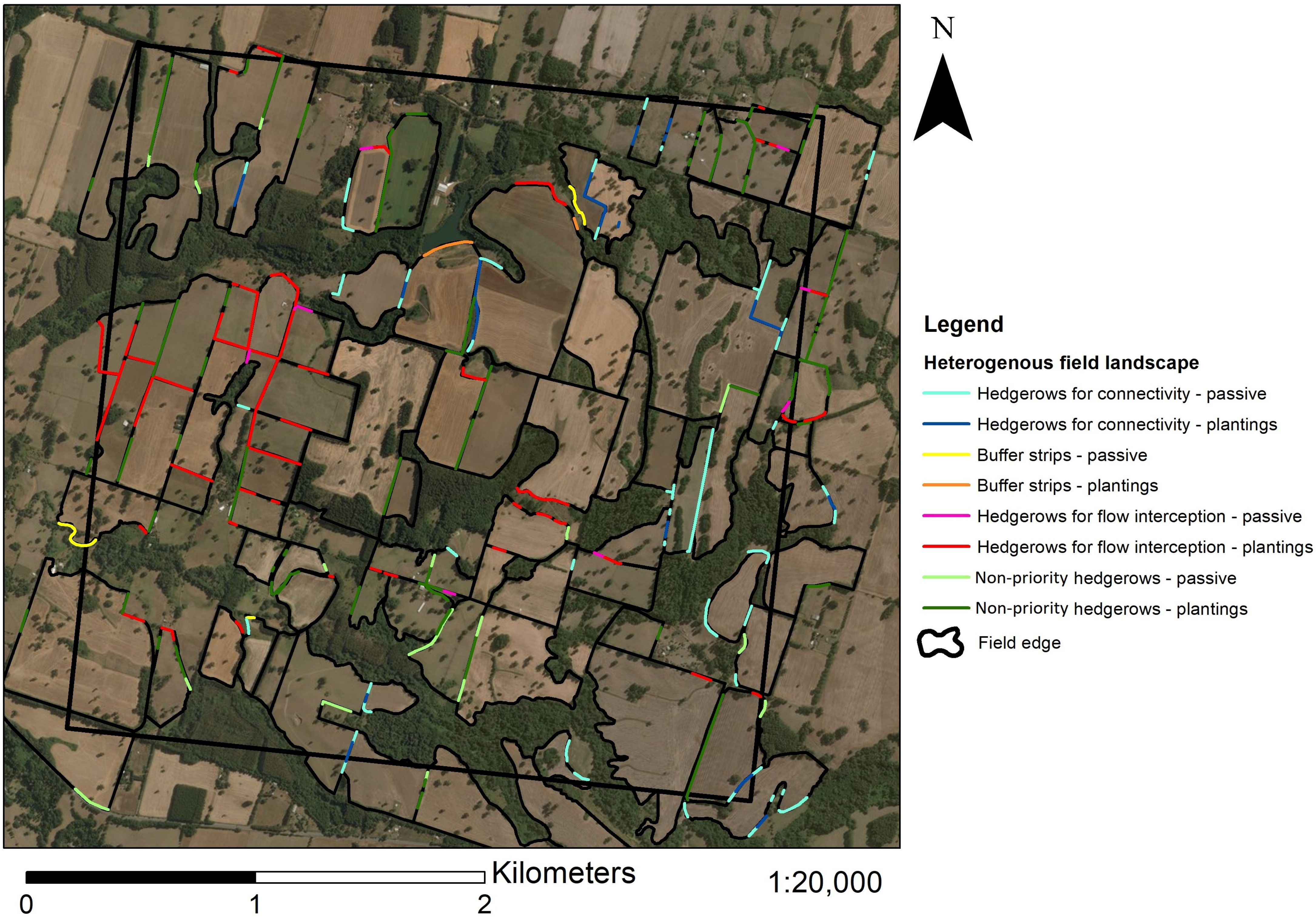
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Legend
Heterogenous field landscape
Hedgerows for connectivity - passive
Hedgerows for connectivity - plantings
Buffer strips - passive
Buffer strips - plantings
Hedgerows for flow interception - passive
Hedgerows for flow interception - plantings
Non-priority hedgerows - passive
Non-priority hedgerows - plantings
Field edge
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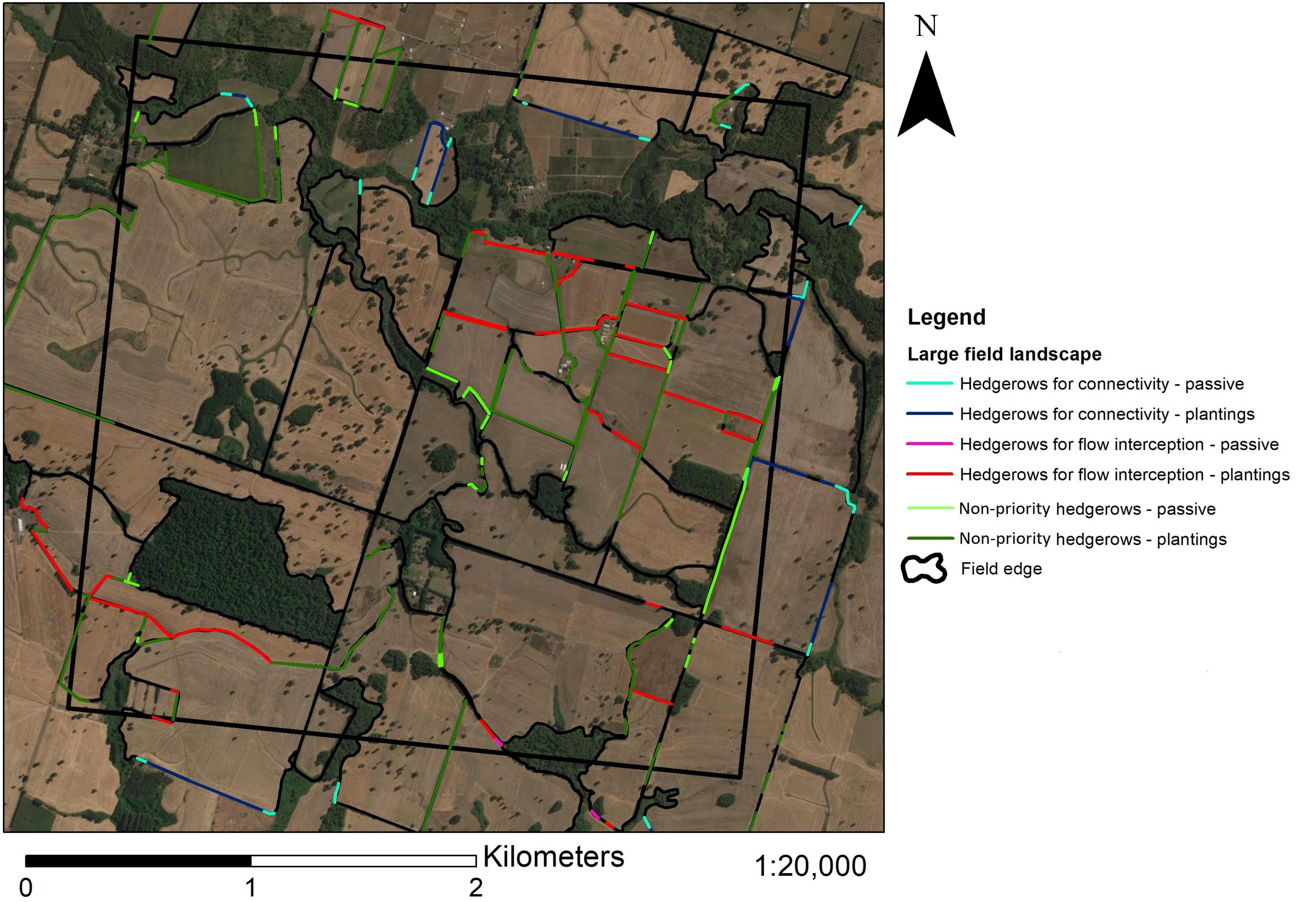
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Large field landscape
Hedgerows for connectivity - passive
Hedgerows for connectivity - plantings
Hedgerows for flow interception - passive
Hedgerows for flow interception - plantings
Non-priority hedgerows - passive
Non-priority hedgerows - plantings
Field edge
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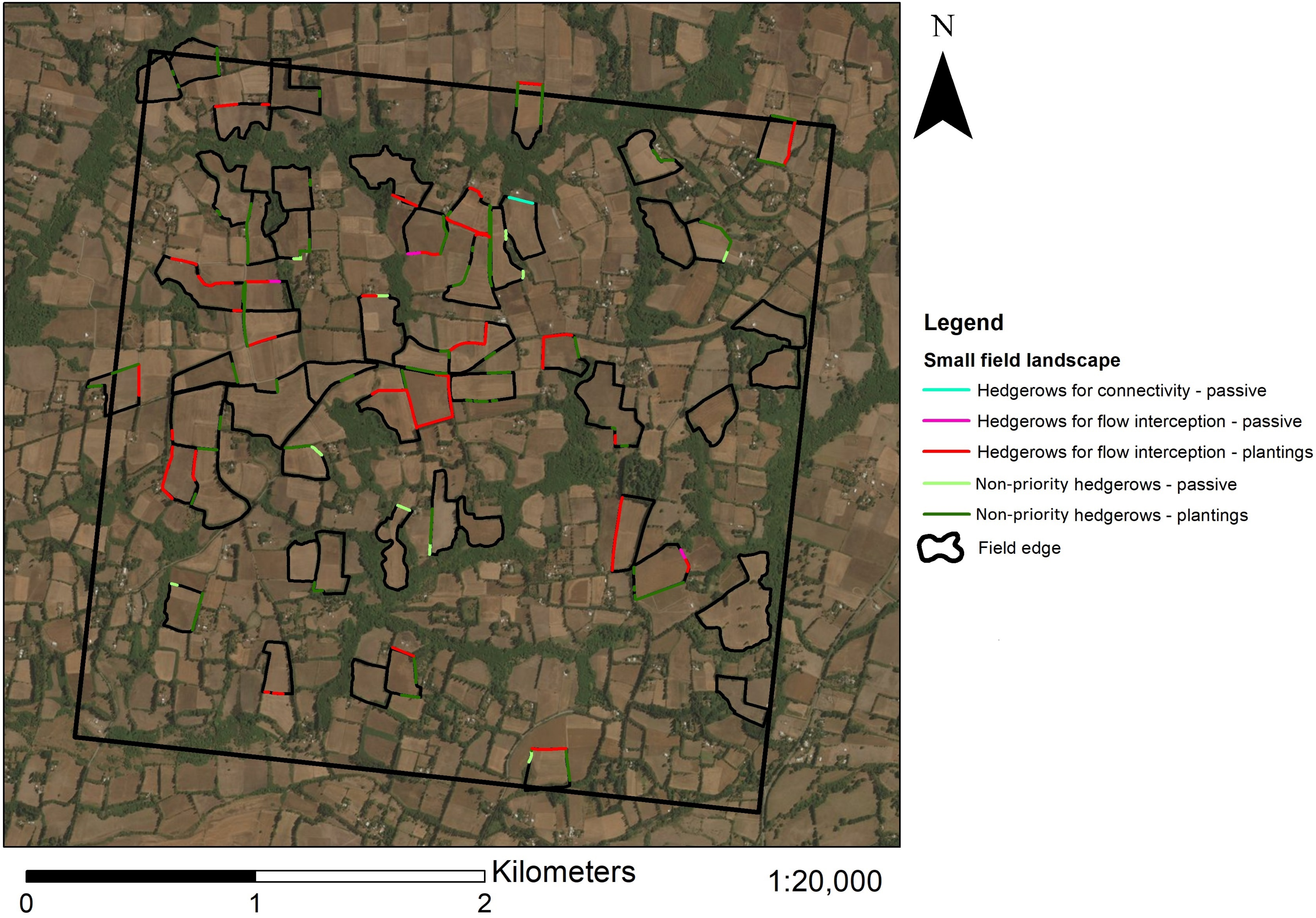

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Legend
Small field landscape
Hedgerows for connectivity - passive
Hedgerows for flow interception - passive
Hedgerows for flow interception - plantings
Non-priority hedgerows - passive
Non-priority hedgerows - plantings
Field edge
Kilometers
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Ambio

Supplementary Material

This supplementary material has not been peer reviewed.

Title: Landscape restoration in a mixed agricultural-forest catchment: planning a buffer strip and hedgerow network in a Chilean biodiversity hotspot

Appendix S1 – Suplementary Material and Methods

Detailed characterization of agricultural landscapes

As the Chilean law (principally Law 20.283 of 2008 and the related Decret no. 82 of 2011; Romero et al., 2014) pursues the conservation of all buffer strips, we first used the official Chilean *Dirección General de Aguas* (2010) drain network layer, which was geographically corrected prior to digitalization, to identify all water courses in the catchment. We measured with QGIS (2004-2016) the length and the width of existing buffer strips, both woody and herbaceous, at 500 points randomly distributed along these water courses, which were previously delineated and digitized on Google Earth® imagery with Google Earth Pro® (2015) tools. The length was measured in two 250-m segments, one upstream and the other one downstream, from each of the 500 random points, and the width –excluding "open water" with no canopy cover- was measured at the perpendicular axis of the river or stream at these points. For this task, the shadows were not a potential source of error because we could distinguish well the delineated figures from their shadows.

The visual inspection of Google Earth® imagery allowed us to distinguish three major types of agricultural landscapes that noticeable differed in their field size and presence of woody vegetation elements (**Table S1**). To characterize the agricultural landscapes, we selected a total of 80 individual fields in the catchment that were digitalized. Of those 80 fields, 20 were randomly distributed throughout the entire catchment. We next selected three 5x5-km areas that were representative of the agricultural landscapes types, and each received 20 random samples (i.e., individual fields) as well, which was deemed a sufficient sample to characterize the target landscape features.

In the three 5x5-km representative agricultural landscapes, we identified the following woody vegetation elements: buffer strips, hedgerows, tree lines, native forest remnants, and exotic tree plantations. Using Q-GIS (2004-2016) software, we measured the following features for each agricultural field: (1) buffer strip, (2) hedgerow and (3) tree line length, (4) buffer strip and (5) hedgerow width, (6) no. of forest remnants within and adjacent to the fields, (7) forest remnant area within the field, (8) forest remnant edge to the field, (9) no. of exotic tree plantations within and adjacent to the fields, (10) tree plantation area within the fields, (11) tree plantation edge to the field, and (12) no. of isolated tress. We distinguished two types of native forest remnants based on their area, namely < and ≥ 0.5 ha. The width of the hedgerows and buffer strips at each field was measured at 10 random points for each element and then averaged per field where they occurred.

Details on survey of woody plant communities

We surveyed in the field the woody plant community composition of the five vegetation elements mentioned above. The survey was performed on 45 individual fields, which were randomly selected from the three 5x5-km areas that were representative of the agricultural landscapes types (15 surveyed fields per 5x5-km area) and digitilized.

At each field, one 20x3-m plot was randomly placed at each occurring woody vegetation element; the number of plots per field ranged between 1 and 4 (mean ± sd = 2.2 ± 0.9; mode = 3 plots). One side of the plot coincided with the crop-edge always. We surveyed a total of 102 plots on hedgerows (31 plots), buffer strips (28, of which 5 were deemed of good ecological condition and 23 were of degraded condition, see Results), tree lines (16), edges of native forest remnants (17), and edges of tree plantations (10). In each 20x3-m plot we measured the occurrence, number of individuals, dbh, and height of all shrubs and trees with dbh ≥ 5 cm or height ≥ 1.3 m.

We calculated mean species richness and number of individuals per plot and the Importance Value Index (IVI, which is based on species relative density, relative frequency and relative basal area across plots) of the surveyed shrub and tree species for all 102 sampled plots and for the plots surveyed at each of the various woody vegetation elements. The good ecological condition buffer strips and edges of native forest remnants plots were used as reference plant communities to design the planting modules.

The plant species (basal area) x plot matrix was ordinated (Non-Metric Multidimensional Scaling, NMDS, Legendre and legendre 1993) to visually explore plant community composition at the vegetation elements. We also took advantage of six 500x2-m transects located in five native forest remnants > 2 ha and one 87-m wide good condition buffer strip that were surveyed at Freire municipality –located in the southwetsern part of the study catchment- in the year 2015 by A. A. as a task of another project (ref. FONDECYT 1141294).

Appendix S2 – Supplementary Results

Characterization of agricultural landscapes

The three major types of agricultural landscapes showed an agregated pattern throughout the studied catchment (**Figure S1**). They were: Large fields without or relatively low hedgerow presence (6 m ha^{-1}) (**Figure S2A; Table S1A**); Small fields where hedgerow presence was usually noticeable (118.2 m ha^{-1}) (**Figure S2B; Table S1B**); and fields of Heterogenous and intermediate area where the presence of hedgerows was intermediate between the two other field types (**Figure S2C; Table S1C**). Buffer strips by the water courses and remnants of native forests, exotic tree plantations, and isolated trees to provide shade to cattle and sheep were often present in the landscapes (**Table S1**).

Composition of woody plant communities

Our survey of woody plant community composition resulted in a list of 33 shrub and tree species, of which 20 (40.6%) were native and 13 (39.4%) were exotic - and seven of them, including *Ulex europaeus*, *Acacia dealbata* and *Pinus radiata,* can be considered as highly invasive species (Fuentes et al. 2014). Mean species richness and mean density per 20x3-m plot were 1.74 ± 1.12 (SD) species and 6.13 ± 5.78 individuals (i.e. 1021.7 individuals per ha), respectively. Across all plots, only five native species ranked above the average IVI, namely *Nothofagus obliqua*, *Myrceugenia exsucca*, *Aristotelia chilensis*, *Laurelia sempervirens*, and *Maytenus boaria* (decreasing order; **Table S4**).

Reference buffer strips were dominated by *N. obliqua*, *Drimys. winteri* and *A. chilensis*, and degraded buffer strips by *N. obliqua* and *M. exsucca* (**Table S4**). Hedgerows and edges of native forest remnants were dominated by *N. obliqua, L. sempervirens,* and *A. chilensis*; however, the exotics *Populus nigra* and *Acer pseudoplatanus* were also important in hedgerows and native forests, respectively (**Table S4**). Nine native species occurring at edges of native forest remnants – principally *Lomatia dentata* and *D. winteri* - did not occur at the hedgerows (**Table S4**). Only four out of the 14 species found at tree lines were native; the dominant species were *Eucalyptus globulus*, *Pseuodtsuga mienzesii, Pinus radiata*, *M. boaria*, *Populus alba*, and *P. deltoides*. *E. globulus* and *P. radiata*, were dominant at the edges of tree plantations, which only exhibited two native species of marginal importance (**Table S4**). The NMDS plot of plant composition revealed a relatively dispersed pattern of native plant species at reference buffer strips and edges of native forest remnants (**Figure S3**) and mostly an aggregated pattern of exotic plant species at tree lines and exotic tree plantations (detailed results not shown).

The 500x2-m transects located in the five native forest remnants >2 ha and the reference buffer strip provided a list of 22 shrub and tree species (three exotics; **Table S5**).

In short, all surveys together identified a total of 42 shrub and tree species, 27 of which were native. Of those 27 species, *N. obliqua, D. winteri*, *L. sempervirens,* and *A. chilensis,* had IVI above the average at reference sites, whereas *Persea lingue*, *M. boaria*, *L. dentata,* and *Rhaphithamnus spinosus* also attained some importance at these sites. Finally, 19 species did not occur or were of marginal importance at the reference sites.

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Table S1. Summary figures (mean ± SD) of agricultural field features for major types of agricultural landscapes and for all fields in the catchment. [1]Calculated for 20 sampled fields of three 5x5 representative agricultural landscapes. [2]Calculated for 20 random sampled fields across the entire catchment. [3]Averaged for those fields with occurrence of buffer strips and/or hedgerows; note that this width is usually shared by two contiguous fields. [4]Only one field had a 90.5-m long buffer strip.

	[1]"Large" field type	**[1]"Small" field type**	**[1]"Heterogenous" field type**	**[2]Catchment**
Field area (ha)	74.14 ± 76.01	2.47 ± 2.23	14.75 ± 14.00	19.77 ± 14.93
Hedgerow length (m)	443.58 ± 555.49	292.04 ±173.24	382.75 ± 434.98	413.03 ± 510.99
Tree line length (m)	173.90 ± 302.91	57.56 ±70.47	33.81 ± 101.10	117.47 ± 192.57
Buffer strip length (m)	650.75 ± 1507.48	[4]NA	148.01 ± 433.88	100.85 ± 335.88
[3]Hedgerow width (m)	23.86 ± 14.19	14.28 ± 6.81	21.53 ± 13.48	16.66 ± 8.27
[3]Buffer strip width (m)	44.54 ± 26.63	[4]NA	68.03 ± 30.68	45.60 ± 25.94
No. of interior forest remnants	1.60 ± 1.82	0.10 ± 0.31	0.50 ± 0.83	0.50 ± 1.00
Area of interior forest remnants (ha)	4.98 ± 8.30	0.02 ± 0.07	0.30 ± 0.70	0.20 ± 0.37
Edge of of interior forest remnants (m)	1388.95 ± 1964.71	23.86 ± 95.76	161.80 ± 279.84	139.30 ± 256.39
Edge of of adjacent forest remnants (m)	392.67 ± 817.48	19.50 ± 48.30	266.41 ± 316.15	264.35 ± 349.62
No. of interior tree plantations	0.90 ± 2.02	NA	0.15 ± 0.37	0.10 ± 0.45
Area of interior tree plantations (ha)	1.28 ± 3.85	NA	0.05 ± 0.13	0.04 ± 0.13
Edge of of interior tree plantations (m)	560.3 ± 1572.82	NA	39.10 ± 83.92	16.15 ± 72.22

Edge of of adjacent tree plantations (m)	16.58 ± 74.13	8.42 ± 37.67	51.90 ± 78.58	105.00 ± 183.31
No. of isolated trees	17.50 ± 19.21	0.65 ± 1.27	9.65 ± 9.86	18.55 ± 24.31

Table S2. Native species that are available in four nurseries[1] within the study area and their price (USD in June 2017). An empty cell means that a particular species is not available in that nursery. Complementary information related to the evergreen (E) or deciduous (D) character, successional stage (E: Early, L: Late) and phenology of flowering and fruting (A: Autumn, Sp: Spring, Su: Summer, W: Winter) according to Donoso (2013) and Riedmann et al. (2014) is reported. Eighteen of these species were not captured by our field surveys.

	Temuco 1 (USD)	**Temuco 2** (USD)	**Cunco** (USD)	**Freire** (USD)	**Average** (USD)	**Evergreen/ Deciduous**	**Successional Stage**	**Flowering**	**Fruiting**
Trees									
Aextoxicon punctatum		4.40		2.40	3.40	E	L	Sp	Su-A
Amomyrtus luma		4.70			4.70	E	E	Sp	Su
Amomyrtus meli			4.00	2.40	3.20	E	L	Sp	Su-A
Araucaria araucana		1.30			1.30	E	L	Su	A
Aristotelia chilensis		3.20			3.20	E	E	Sp-Su	Su
Austrocedrus chilensis			3.20		3.20	E	L	Sp	Su
Caldcluvia paniculata			4.00	3.20	3.60	E	L	Su	W
Cryptocarya alba				2.40	2.40	E	L	Sp	W
Drimys winteri			7.90	2.80	5.40	E	E	Sp	Su
Embothrium coccineum		2.40		1.60	2.00	E	E	Sp	Su
Eucryphia cordifolia			4.00		4.00	E	L	Su	A
Fitzroya cupressoides	6.30				6.30	E	E	Sp-Su	Su-A
Gevuina avellana		2.40	4.70	2.80	3.30	E	I	Sp	Su
Laurelia sempervirens		3.00	3.20	2.40	2.80	E	I	Sp	Su
Lomatia dentata		3.20			3.20	E	I	Su	W
Lomatia hirsuta				2.40	2.40	E	E	Sp	Su
Luma apiculata			4.70	2.40	3.60	E	I	Su	Su-W
Maytenus boaria		4.00		3.20	3.60	E	E	Sp	Su-W
Myrceugenia exsucca				2.40	2.40	E	L	Su	W

Nothofagus dombeyi	3.50		3.20	2.80	3.20	E	E	Sp	Su
Nothofagus nervosa	3.20	2.40	3.20	2.80	2.90	D	E	Sp	Su-A
Nothofagus obliqua	4.00		3.20	2.80	3.30	D	E	Sp	Su
Persea lingue		2.40		3.20	2.80	E	I	Sp	Su-A
Peumus boldus		2.40		2.40	2.40	E	L	Sp	Su
Podocarpus nubigena		3.20	4.70	3.20	3.70	E	L	Sp	A
Prumnopitys andina			3.20		3.20	E	I	Sp	Su-W
Quillaja saponaria		2.80		2.40	2.60	E	E	Su	Su-W
Sophora microphylla		3.20			3.20	E	E	Sp	A
Weinmannia trichosperma			4.70	3.20	4.00	E	L	Sp-Su	Su
Shrubs									
Buddleja globosa		3.40			3.40	E	E	Sp	A
Calceolaria dentata		4.00			4.00	E	E	Sp	Su
Fuchsia magellanica		2.40			2.40	E	E	W-A	A-Sp
Mitraria coccinea		4.00			4.00	E	L	Sp-Su	Su
Ugni molinae		2.40			2.40	E	E	Sp-Su	Su

[1]The names are related to the city and towns were the nurseries are located. Temuco 1 is the Centro de Gestión Bachmann y Bachmann; Temuco 2 is the Universidad de la Frontera nursery; Freire is the Vivero Los Robles (URL: www.viverolosrobles.com); Cunco is the Vivero Los Troncos (URL: www.lostroncosf10.com).

Table S3. Species richness and density (mean ± SD) per 20x3-m plot surveyed at the various woody vegetation elements.

Woody vegetation element	Species richness	Density
Reference buffer strips	3.4 ± 0.89	7.8 ± 3.77
Degraded buffer strips	1.39 ± 0.58	6.82 ± 8.61
Hedgerows	1.19 ± 0.48	2.13 ± 1.63
Tree lines	1.43 ± 0.96	9.0 ± 4.23
Edges of native forests	1.65 ± 0.86	7.12 ± 4.33
Edges of tree plantations	2.4 ± 0.52	9.8 ± 4.39

Table S4. List of species surveyed at 102 20x3-m field plots distributed on 45 fields (15 in each representative agricultural landscape). Note: the columns all plots, hedgerows, and degraded buffer strips do not add 100 due to a few plots without species that attained the minimum survey measures. Superscripts mean S shrub, T tree, and E exotic.

Species	**Importance Value Index (%)**						
	All	Reference buffer strips	Degraded buffer strips	Edges of forest remnants	Hedgerows	Tree lines	Edges of tree plantations
Acacia dealbata^{TE}	0.3					1.5	
Acacia melanoxylon^{TE}	2.2					4.3	11.3
Acer pseudoplatanus^{TE}	2.2	4.6		6.2		2.9	
Aextoxicon punctatum^{T}	0.3			1.7			
Aristotelia chilensis^{T}	4.5	6.7	1.9	7.3	8.9		7.2
Azara integrifolia^{S}	0.3		3.7	1.6			
Blepharocalyx cruckshanksii^{T}	0.8						
Buddleja globosa^{S}	0.3	2.9					

Dasyphyllum diacanthoides[T]	0.3	2.9					
Drimys winteri[T]	2.1	21.7	1.3	3.4			
Eucalyptus globulus[TE]	7.7				2.6	20.2	27.8
Eucalyptus nitens[TE]	0.8						6.3
Eucryphia cordifolia[T]	0.4			2.0			
Laurelia sempervirens[T]	4.5	3.2		8.6	15.3		
Laureliopsis philippiana[T]	0.3			1.6			
Lomatia dentata[T]	0.7			3.7			
Luma apiculata[T]	0.4		1.7				
Maytenus boaria[T]	3.4	7.1	1.5		6.6	8.6	
Myrceugenia exsucca[T]	7.2		30.5	1.8			
Nothofagus dombeyi[T]	2.0	37.3	5.8	2.1	3.5		
Nothofagus obliqua[T]	31.3	5.9	41.9	52.8	22.6	4.2	6.0
Persea lingue[T]	1.6		1.7	1.8	2.5		
Peumus boldus[T]	0.3					1.5	
Pinus radiata[TE]	7.8			1.6		20.7	26.7
Populus alba[TE]	2.1					9.8	
Populus deltoides[TE]	1.3					6.7	

Populus nigra^{TE}	2.0				7.6	3.8	4.6
Pseudosuga menziesii^{TE}	3.6					10.6	10.1
Rhamnus diffusus^{S}	0.3			1.6			
Raphithamnus spinosus^{T}	1.3	3.8	1.2	2.2		1.5	
Salix caprea^{TE}	1.4	4.1			2.1	3.7	
Salix humboldtiana^{TE}	0.8		3.9				
Ulex europaeus$^{S.E}$	0.4				2.5		

Table S5. List of species found at six 500x2-m transects located in five forest remnants > 2 ha and one buffer strip of good condition and their Importance Value Index. Superscript S means shrub, T tree, and E exotic.

Species	**IVI (%)**
Quercus petraea[T,E]	13
Chusquea quila[S]	11
Aristotelia chilensis[T]	8
Drimys winteri[T]	7
Embothrium coccineum[T]	6
Luma apiculata[T]	6
Myrceugenia exsucca[T]	6
Maytenus boaria[T]	5
Gevuin avellana[T]	5
Nothofagus dombeyi[T]	4
Persea lingue[T]	3
Gaultheria mucronata[S]	3
Ugni molinae[S]	3
Berberis darwinii[S]	3
Raphithamnus spinosus[T]	3
Laurelia sempervirens[T]	2
Eucryphia cordifolia[T]	2
Lomatia dentata[T]	2
Ulex europaeus[S,E]	1
Ribes magellanicum[S]	1
Greigia sphacelata[S]	1
Rubus ulmifulius[S,E]	1

Table S6. Estimated budget breakdown for buffer strip and hedgerow plantings, in USD. [1]The prices of the cheapest seedlings in **Table S2** was reduced by 25% due to discount for purchasing >100 seedlings per species, according to information from the nurseries. [2]The transportation cost was calculated on the basis of USD 1.58-2.40 km^{-1}, an average of 27.5 km per transport, and 2667 or 2500 seedlings per transport to plant 1 ha of buffer strip or hedgerow, respectively ([3]Note: the transportation costs per planted module and ha of buffer and hedgerow are similar despite the number of planted seedlings differing because of the total amounts of planted seedlings that can fit in a truck load).

Item budget	**Unit**	**Amount**	**Cost range**		**Mid value**
[1]Seedlings			Min	Max	
Buffer strip					
N. obliqua	Individual	5	2.10		
D. winteri	Individual	3	2.10		
L. sempervirens	Individual	1	1.80		
A. chilensis	Individual	2	2.40		
P. lingue	Individual	2	1.80		
M. boaria	Individual	2	2.40		
B. globosa	Individual	1	2.55		
Buffer strip	Module (16 seedlings)	1	34.35		
Buffer strip	Ha (2667 seedlings)	1	5725		
Hedgerow module 1					
N. obliqua	Individual	8	2.10		
L. sempervirens	Individual	3	1.80		
A. chilensis	Individual	2	2.40		
L. dentata	Individual	2	2.40		
	Module (15 seedlings)	1	31.80		
	Ha (2500 seedlings)	1	5300		
Hedgerow module 2					
N. obliqua	Individual	8	2.10		
D. winteri	Individual	3	2.10		
P. lingue	Individual	2	1.80		
A. punctatum	Individual	2	1.80		
	Module (15 seedlings)	1	30.30		
	Ha (2500 seedlings)	1	5050		
Hedgerow module 3					
N. obliqua	Individual	8	2.10		
E. cordifolia	Individual	3	3.00		

M. exsucca	Individual	2	1.80		
N. dombeyi	Individual	2	2.10		
	Module (15 seedlings)	1	33.60		
	Ha (2500 seedlings)	1	5600		
[2]Plant transportation	Buffer strip seedling	1	0.016	0.024	0.02
	[3]Buffer strip module	1	0.261	0.391	0.326
	[3]Buffer strip ha^{-1}	1	43.44	65.17	54.30
	Hedgerow seedling	1	0.017	0.026	0.022
	[3]Hedgerow module	1	0.261	0.391	0.326
	[3]Hedgerow ha^{-1}	1	43.44	65.17	54.30
Plant protectors	Unit	1	0.24	0.27	0.255
	Buffer strip module	1	3.84	4.32	4.08
	Buffer strip ha^{-1}	1	640.10	720.10	680.10
	Hedgerow module	1	3.60	4.10	3.85
	Hedgerow ha^{-1}	1	600	675	637.50
Planting (labour)	Planted seedling	1	0.26	0.44	0.35
	Buffer strip module	1	4.21	7.02	5.615
	Buffer strip ha^{-1}	1	702.21	1170.24	936.22
	Hedgerow module	1	3.95	6.58	5.26
	Hedgerow ha^{-1}	1	658.24	1097.10	877.67
Total buffer strip	Module		42.66	46.08	44.37
	Ha		7111	7681	**7396**
Total hedgerow 1	Module		39.61	42.87	41.24
	Ha		6602	7137	**6869**
Total hedgerow 2	Module		38.11	41.37	39.74
	Ha		6352	6887	**6619**
Total hedgerow 3	Module		41.41	44.67	43.04
	Ha		6902	7437	**7169**

Figure legends

Figure S1. Methodological approach to plan the restoration of a buffer strip and hedgerow network.

Figure S2. Images corresponding to the 5x5-km agricultural landscapes representative of Large (A), Small (B) and Heterogenous (C) fields.

Figure S3. Ordination diagramme of woody plant communities according to the NMDS performed on all surveyed 20x3-m field plots. The dominant species at plots that represent reference buffer strips and edges of native forest remnants are highlighted. See **Table 4S** for plant name initials.

Fig. S1

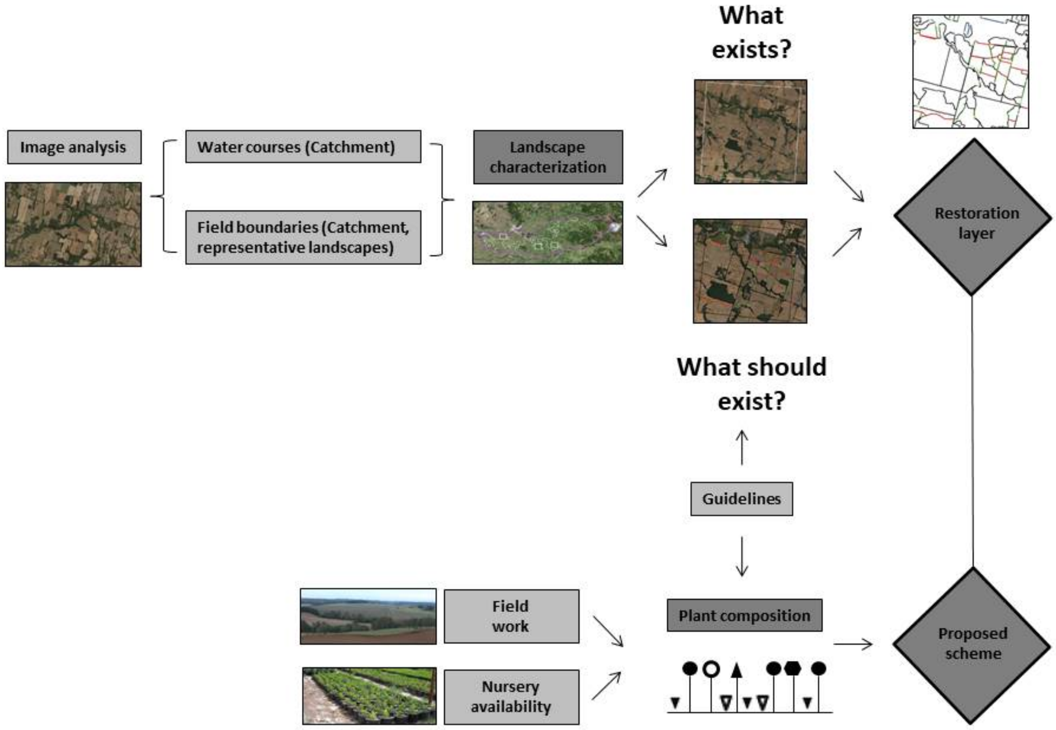

Fig. S2-A

Fig. S2-B

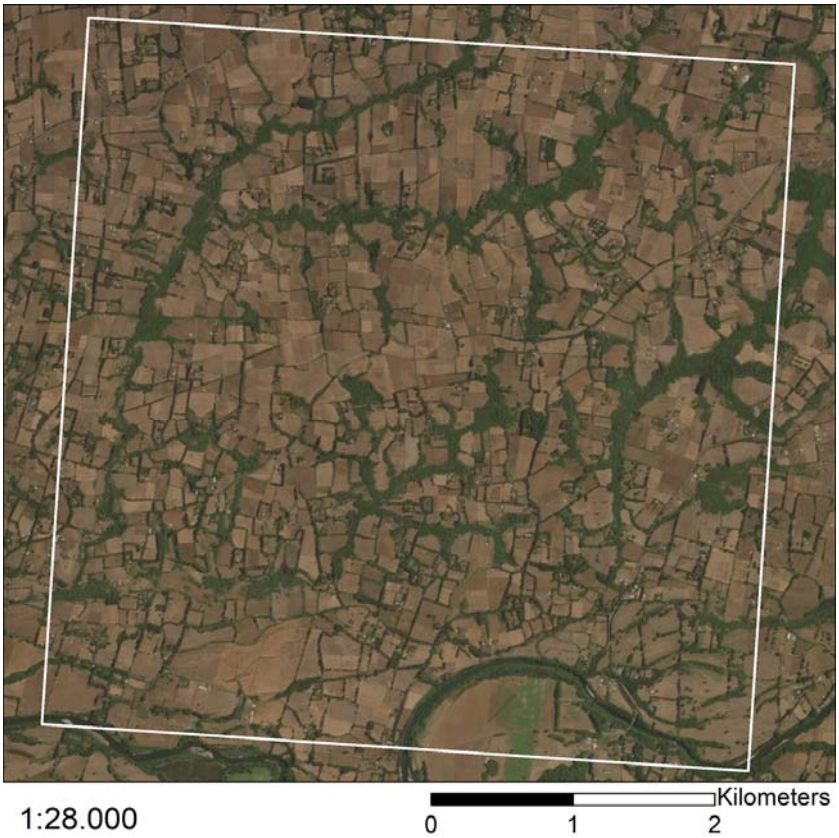

Fig. S2-C

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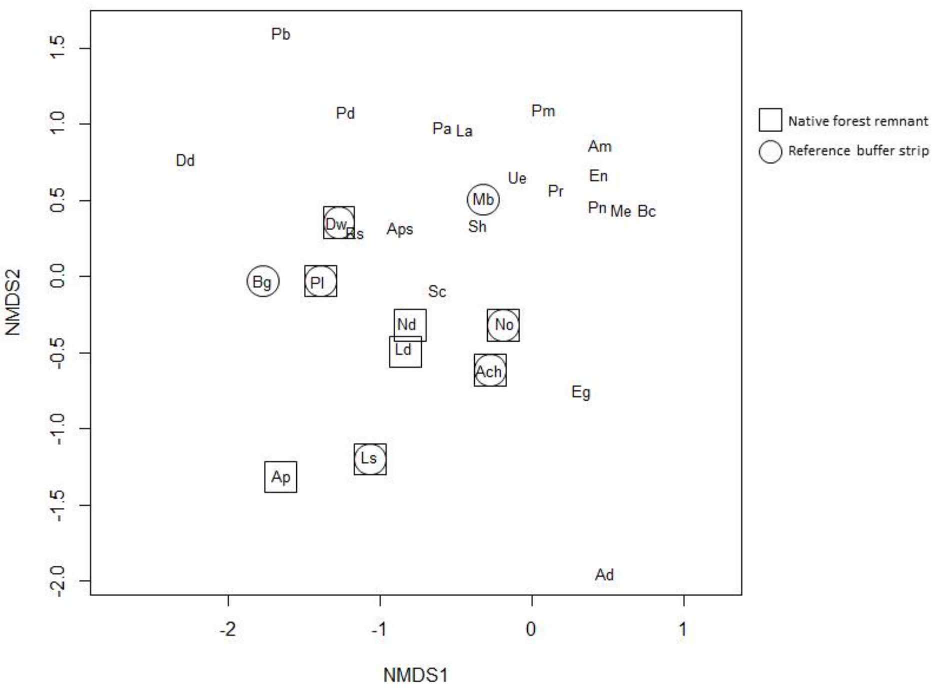

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