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Quantifying impact reduction due to avoidance, minimization and restoration for a natural gas pipeline in the Peruvian Andes

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ABSTRACT

We present monitoring methods and quantitative biodiversity data to document components of the mitigation hierarchy. We estimated avoidance, minimization, restoration and impact reduction in quality hectares for the 25 m wide right of way of a 408 km natural gas buried pipeline that crosses 14 Ecological Landscape Units (ELUs) in the tropical Andes of Peru. We found that applying the mitigation hierarchy as part of a comprehensive biodiversity action plan substantially reduced impacts on biodiversity in all habitats studied. Avoidance and right of way minimization contributed to significant impact reduction. We quantified impact reduction during construction and operation on the right of way of the pipeline over a five-year period and found that restoration was the greatest contributor to reducing impacts. We documented that most ELUs have a positive restoration trajectory. We also documented how monitoring over large scale spatial scales, in combination with site-specific monitoring, generated data for management to determine restoration priorities and impact mitigation. A biodiversity action plan that incorporated the mitigation hierarchy and a science-based biodiversity monitoring and assessment program contributed to biodiversity management of the project and played an important role in minimizing and managing impacts.

1. Introduction

As infrastructure and development projects continue to be implemented worldwide (Battacharya et al. 2012), biodiversity rich areas are increasingly at risk of experiencing negative impacts on biodiversity and ecosystems services (Benchimol and Peres 2015, Finer et al. 2008, Winemiller et al. 2016). Reducing impacts due to project design and construction is a critical component of conservation and development, and entails participation and investment in funds and expertise by the public, private, and non-profit sectors (Business and Biodiversity Offsets Programme 2012, Saenz et al. 2013) as well as “mainstreaming” biodiversity conservation and management outside of protected areas (Redford et al. 2015).

Several strategies have been proposed to implement best-practices and mitigate project impacts to safeguard biodiversity and attain “no net loss” (Business and Biodiversity Offsets Programme 2012, Villarroya et al. 2014). In addition to the Environmental and Social Impact Assessments (ESIA) as a tool to determine the potential impacts on biodiversity (Energy and Biodiversity Initiative 2003), the project-lending sector is providing standards for biodiversity and ecosystem services standards and implementation of the mitigation hierarchy (International Finance Corporation 2012, World Resources Institute 2008).

The mitigation hierarchy framework is a best-practice approach for development projects that manages risks and potential impacts to biodiversity and ecosystem services (Cross Sector Biodiversity Initiative, 2015). It encompasses four components that can contribute to reduce, manage and offset project impacts: avoidance of sensitive habitat, minimization of impacts, restoration of habitat, and offsetting project impacts if necessary. Avoidance measures are taken to prevent impacts from the planning and beginning of a project and may include modifications in spatial or temporal placement of elements of the infrastructure to minimize impacts. Minimization includes measures taken to reduce the duration, intensity and/or extent of impacts that cannot be avoided. Restoration measures are those taken to restore impacted ecosystems following exposure to impacts not avoided or minimized

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and are a response variable to avoidance, minimization and adaptive management efforts. Finally, offsets as a last resource, are measures taken to compensate for any residual, significant, adverse impacts that cannot be avoided, minimized and/or restored/rehabilitated, in order to achieve no net loss or a net gain in biodiversity (Business and Biodiversity Offsets Programme 2012).

Although a stated condition for offsets is that the mitigation hierarchy be applied first (International Finance Corporation 2012), and offsets be utilized as a last result, little qualitative and quantitative information exists on the application of the mitigation hierarchy prior to offset design (Kiesecker et al. 2010). The application of offset measures has received a lot of attention with regard to the mitigation hierarchy (Gardner et al. 2013, The Biodiversity Consultancy and Fauna and Flora International, 2012a, b, Villarroya et al. 2014), yet application of offsets is still controversial (Bull et al. 2013, Maron et al. 2012, Quetier et al. 2014), and few studies exist that show their long-term efficacy or sustainability (Curran et al. 2014, Moreno-Mateos et al. 2015). For example, habitat restoration offsets may lead to a net loss of biodiversity (Curran et al. 2014) while a number of theoretical and practical issues ranging from use of appropriate currencies, determining habitat equivalencies, longevity, uncertainty and others (Bull et al. 2013) make designing offsets a challenge. Moreno-Mateos et al. (2015) make the claim that multiple ecological, regulatory and ethical losses can occur when evaluating offsets and argue for greater transparency in documenting biodiversity losses. Because application of avoidance, minimization, and restoration/rehabilitation are critical components of a biodiversity strategy or action plan, and may influence offset planning as well as landscape level land-use planning (Saenz et al. 2013), careful implementation and quantification of the mitigation hierarchy is crucial for biodiversity conservation in the area of influence of a project. Furthermore, quantifying the effects of impacts on species, habitats, and ecological processes becomes indispensable for quantifying residual impacts of a project.

Monitoring programs for indicator species and habitats during all phases of a project is a useful approach to quantify residual impacts and guide restoration decisions (Alonso et al. 2013, Lindenmayer 1999). Habitats and biodiversity can be restored more effectively if project managers utilize monitoring programs within an adaptive management framework, especially when the mitigation hierarchy is applied. When impacts can be reduced and restoration activities are informed by appropriate monitoring techniques that suit the scale of the project, measure appropriate indicators, and assess aspects or proxies of ecosystem functionality, then impact reduction targets and positive restoration trajectories may be attained.

Over a five-year period, we quantified systematic impact reduction during construction and operation of a 408 km long 34″ wide natural gas pipeline in the tropical Andes. The pipeline extends from the eastern Ayacucho Region, traverses the Andes through the Departments of Ayacucho and Huancavelica, and goes into the Pacific slope through the desert of the Departments of Ica and Lima, where a 4.4 million metric tons per annum natural gas liquefaction facility (LNG plant) is located (Fig. 1). Prior to the pipeline construction, 14 Ecological Landscape Units (ELUs) that correspond to mountain systems, drainage basins, and functional attributes and commonalities were assigned to landscapes along the pipeline (Langstroth et al. 2013). Major habitat types ranged from Andean wetlands, grasslands, montane forest, dry forest, scrublands, desert scrub and desert, and altitude ranged from sea level to 4900 m. Avoidance and Right of Way (RoW, the stretch of land to be used for construction and operation of the pipeline) width minimization were quantified for the entire RoW and vegetation restoration was monitored annually for the first 241 km of the pipeline, which corresponded to ELU's 1–11. Site - and species-specific research and monitoring activities were conducted throughout the pipeline (ELU's 1–12) via a partnership between PERU LNG and the Center for Conservation and Sustainability, Smithsonian Institution via their Biodiversity Monitoring and Assessment Program (BMAP).

Herein, we present quantitative data on the mitigation hierarchy. We estimated post-hoc avoidance data due to micro-routing of the final track, and width minimization measures for 408 km of the 25 m wide pipeline RoW as specified in contractor management plans. We also present quantitative restoration estimates that compare plant abundance and diversity of the RoW to control areas. While monitoring restoration, we also assessed effectiveness of impact minimization measures (such as topsoil management, erosion control, etc.). Based on these estimates, we calculated residual project impacts for 241 km of the RoW after five years of pipeline operation. We also present one example of a site-specific monitoring study that examined impacts on small rodent diversity and ecological processes such as seed dispersal and habitat connectivity in addition to vegetation restoration. We illustrate how this data was utilized to inform restoration progress or lack thereof. Data gathered via assessments and monitoring at various spatial scales demonstrated to the company the benefits to avoid and minimize impacts implemented prior to project construction, and how to reduce impacts and to achieve a positive restoration trend for the RoW after construction.

2. Background

The company responsible for the construction and operation of the pipeline is PERU LNG, a consortium formed by Hunt Oil (50%), Shell (20%), SK (20%) and Marubeni (10%). A consortium of lenders that included the Inter-American Development Bank, International Finance Corporation (IFC), Export-Import Bank of the United States of America, and others, funded the project. The aforementioned banks apply environmental and social best practices to their projects. These include policies related to biodiversity protection, especially those pertaining to IFC Performance Standard 6 (PS6), which includes specific guidelines to minimize threats to biodiversity through the application of a mitigation hierarchy (International Finance Corporation 2012). The current PERU LNG project was conceived and designed adhering IFC performance standards as defined in 2006.

In order to more effectively implement the mitigation hierarchy to reduce biodiversity associated risk with pipeline construction, PERU LNG developed a Biodiversity Action Plan (BAP), based on guidelines developed by IPIECA (International Petroleum Industry Environmental Conservation Association 2005). The BAP was designed to incorporate the mitigation hierarchy into planning, construction, and post-construction phases and provide specific implementable actions for the protection and conservation of biodiversity during construction and operation of the pipeline (PERU LNG 2007a). The BAP included evaluation of alternative pipeline routes, implementation of the ESIA (Walsh Peru 2005), detailed and smaller scale Ecological Field Surveys (Domus Consultoria Ambiental 2007) and an Ecological Management Plan for each ELU (Environmental Resources Management 2008). These and specific Ecological Action Plans were implemented at the time of the construction of the pipeline. Contractor management plans were written with specific instructions for operating contractors during the construction phase. The BAP was written to follow Peru's legal environmental and social policies, as well as the IFC PS6 version 2006 (Taborga and Casaretto 2013, Dallmeier et al. 2013). The BAP served as an umbrella document that described the framework on how to apply the mitigation hierarchy to reduce and manage biodiversity risks (Maguire et al. 2010). It also provided a framework for the development and implementation of a comprehensive biodiversity monitoring program (the BMAP) and refined the implementation of a restoration plan. The BMAP was used for impact quantification and monitoring to track restoration. BAP activities taken during the various phases of the PERU LNG project were qualitatively summarized by Taborga and Casaretto (2013) and are illustrated in Fig. 2. While area and habitats avoided during construction of the final pipeline route to due micro-routing and width minimization were not quantified until the present study, quantitative data on restoration were collected immediately after

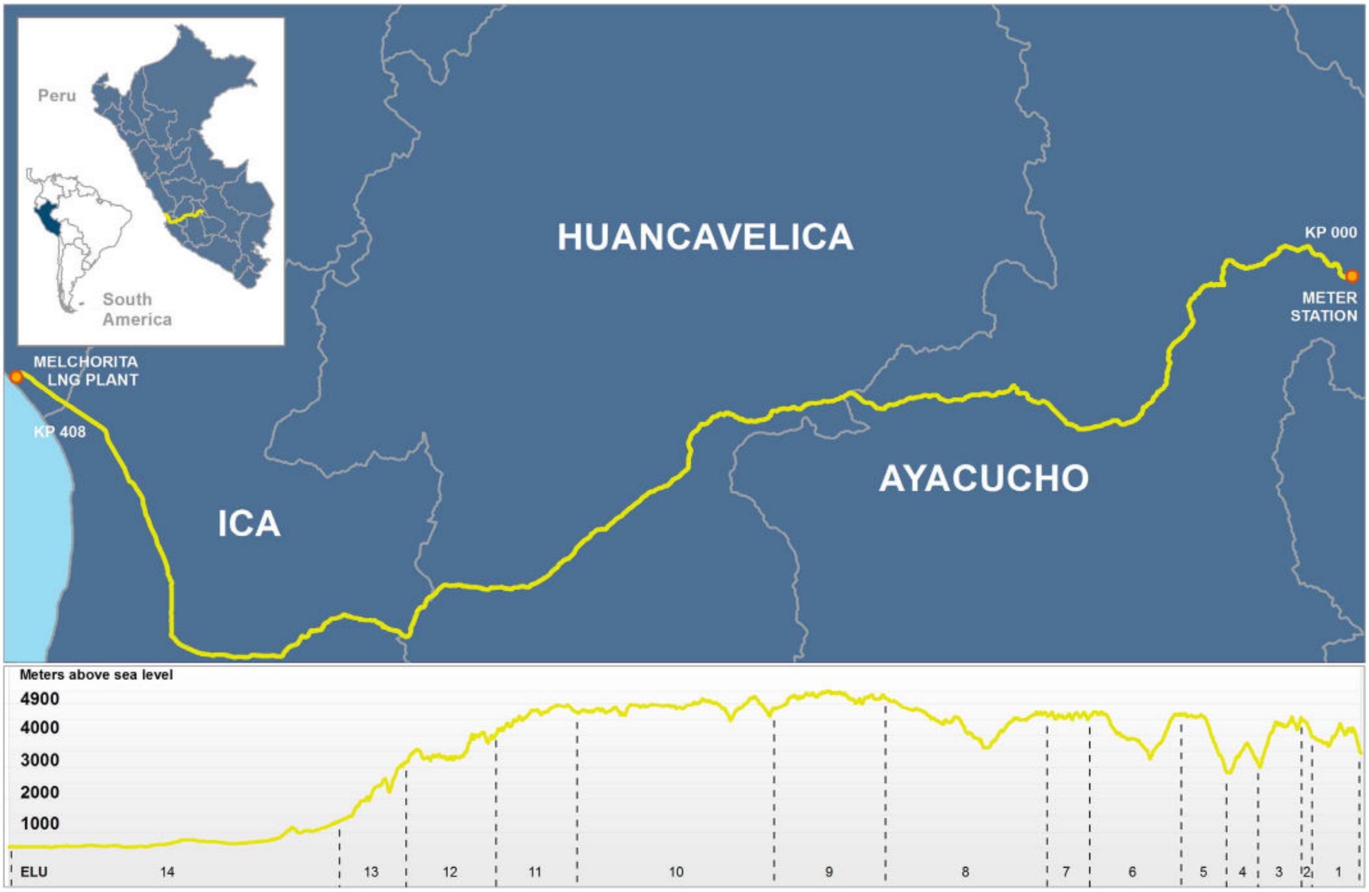

Fig. 1. Map indicating location and topography of the PERU LNG pipeline. Numbers along the bottom represent Ecological Landscape Units 1–14.

construction in 2010 and continue to the present day. The company established restoration targets for impacted areas to attain quality values similar to those of control sites (PERU LNG 2007b).

An offset was not included in project design as it was not required by the Peruvian government or by the lenders. However, the PERU LNG BAP included environmental investment activities to be determined and implemented as needed based on residual impacts and species/habitat priorities. These activities, with the exception of a wild camelid conservation program, were not pre-determined and were designed to be adaptively managed based on needs identified through research and monitoring activities.

The adaptive monitoring framework was designed to be implemented at three spatio-temporal scales with corresponding differences in approach and sampling effort (Fig. 3). Research design for site-specific studies featured an experimental approach that includes both control and impacted sites for selected species of flora and fauna, as well as ecologically and socially sensitive habitats such as Andean wetlands, grasslands and montane forest. Species were selected based on threatened status (national and international), endemism, local abundance, representativeness to the sampled habitat, availability of national specialists, accessibility and safety consideration to reach sampling sites, importance to local people and effectiveness to determine impacts (Alonso et al. 2013).

Sampling effort was determined by research questions and hypotheses tested in peer reviewed protocols developed prior to field work, in contrast to satellite data and large scale point-transect vegetation monitoring. Examples of research questions include: what is the distribution and abundance of the species of interest in the RoW and in the control areas? Are there exotic species present in the RoW? (Alonso et al. 2013). While impacts were predicted for the RoW due to vegetation removal during construction, effects on ecological processes and spatial scale of impacts were unknown. Thus, research questions addressed during and after construction were designed to assess impacts at the construction site as well as in control areas located up to several hundred meters to several kilometers distant. Once the spatial scale of impacts on abundance and diversity were assessed, protocols were adjusted to focus on areas, species, and ecological processes impacted on the RoW (Alonso et al. 2013).

3. Methods

3.1. Vegetation classification and RoW routing changes

We obtained data on habitat types and usage on the RoW and a 400 m wide area of influence (200 m to each side of the RoW) from IKONOS multispectral satellite images with 4 m resolution (fused with a panchromatic band of 1 m spatial resolution). Images were georeferenced and recorded in UTM projection (zone 18, datum WGS 84). We also used a Digital Ground Elevation Model (GDEM) generated with ASTER images of 30 m resolution from the United States Geological Survey.

We interpreted images from Kilometer progressive (Kp) 0 at Chiquintirca-Ayacucho (Coordinates WGS84 640966E 8,556,673 N) to Kp 277 in Ica (Coordinates WGS84 442900E 8,481,796 N) from 2010 through 2014 and from Kp 277 to 408 in Lima (WGS84 359884E 8,535,767 N) in 2011. Habitat polygons were created taking into account form, tone, color, texture, spatial surroundings and additional information such as phenology, presence of cultivars, and field data. We classified polygons into three categories: Habitat type, Land Use and Vegetation cover.

We entered information gathered from satellite images into a GIS (ArcGIS 9.3 and 10.2) and calculated directly the area of habitat types

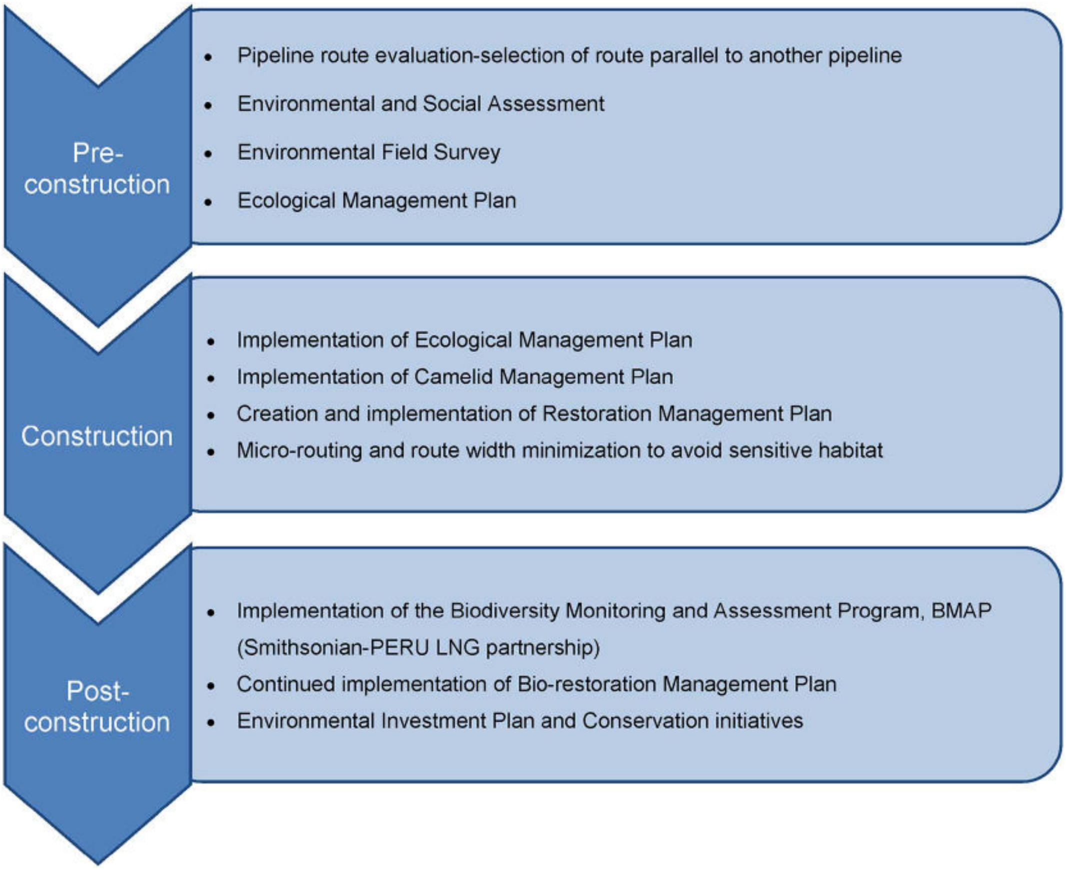

Fig. 2. Implementation of project Biodiversity Action Plan before, during and after construction.

for the RoW. We verified habitat types by contrasting satellite images from 2011, 2012, 2013 and 2014, with Google Earth (version 7.1.2.2041) and yearly vegetation surveys.

To estimate the area that was avoided, micro-routing events were visually assessed using Google Earth, comparing the original route and the modified route. We also estimated pipeline reduction in RoW width using Google Earth. We calculated the area of habitat not impacted due to width minimization efforts during construction of the pipeline RoW (Fig. 4).

3.2. *Assigning biodiversity and ecosystem values to habitats*

We assigned biodiversity and ecosystem significance (BES) values for major habitat classifications affected by the construction of the pipeline (The Biodiversity Consultancy & Fauna and Flora International 2012a). Habitat categories utilized in this analysis were upper montane forest, upper montane scrubland, native grasslands, Andean wetlands (peat-bogs), scrub habitat, desert cactus/scrub, dune vegetation made up of *Tillandsia* mats, and areas of scarce vegetation without priority species. If a habitat category was represented by 0.5 ha or less, we did not include it in our analysis due to lack of accuracy in the image resolution.

We assigned BES values using a combination of biodiversity assessments, recommendations regarding species level of threat and endemism, as well as ecosystem services (provided by wetlands, grasslands, and forests) based on social needs expressed by local communities during the ESIA (Walsh Peru 2005). We also used information from the biodiversity surveys conducted prior to construction such as the Ecological Field Survey and the Ecological Management Plans (Domus Consultoria Ambiental 2007, Environmental Resources Management 2008).

We estimated a BES value for each habitat on a scale from 1 to 5, with one being of lowest significance and five the highest (Table 1). Our values were assigned according to expert judgment and thus are a semi-

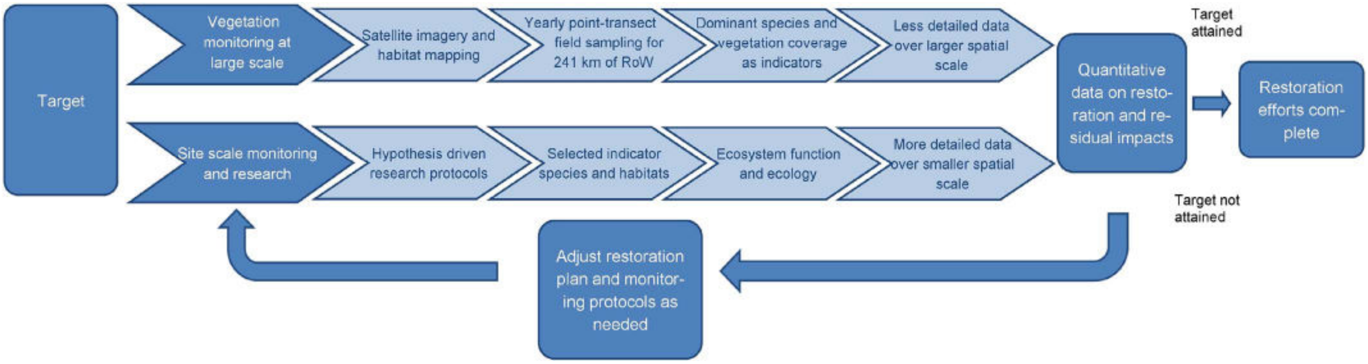

Fig. 3. Adaptive management framework for assessing restoration and reducing impacts.

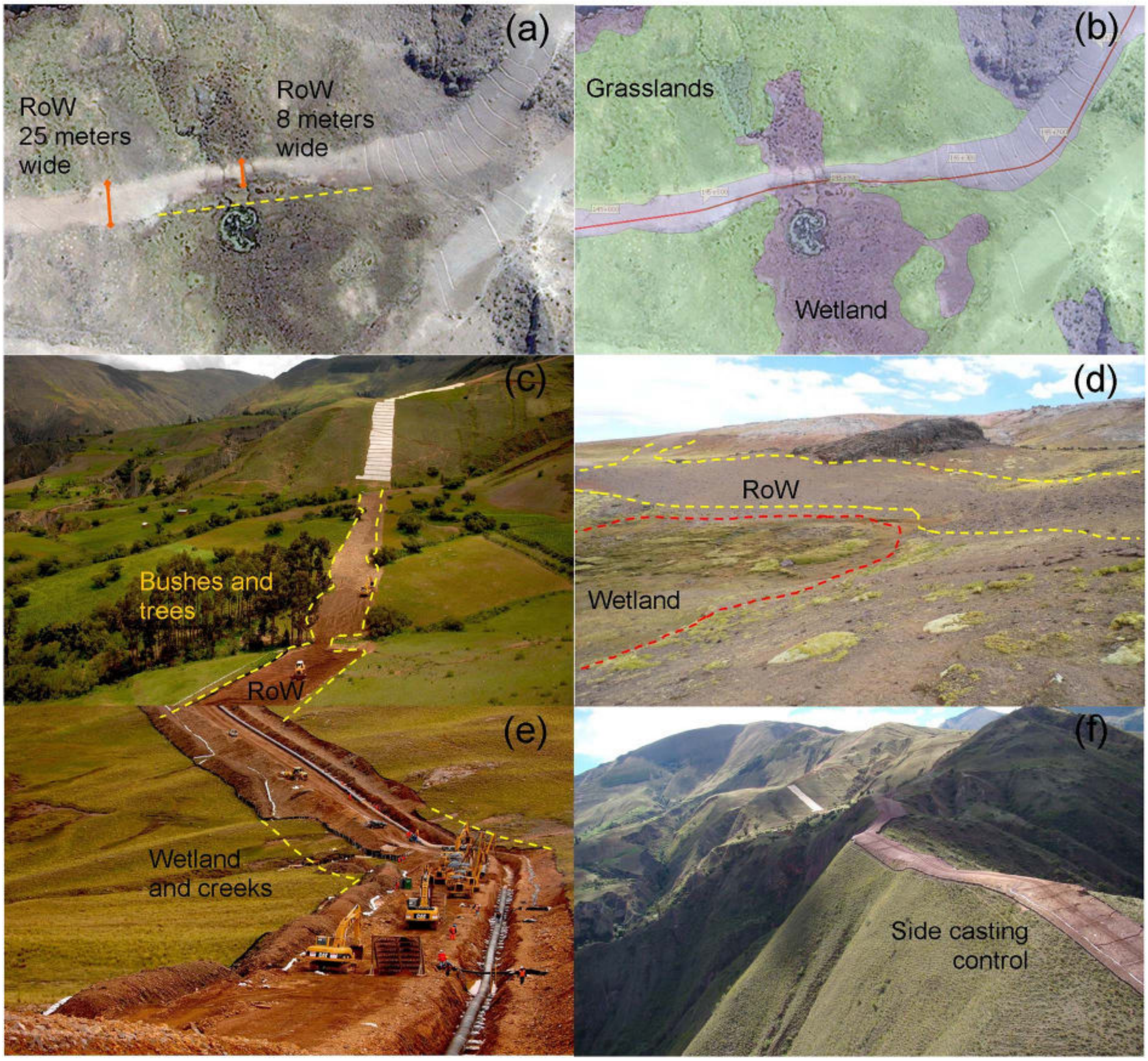

Fig. 4. Images demonstrating some mitigation measures taken during pipeline construction: (a) satellite images of the RoW and (b) images overlaid by polygons of habitat interpretation. These demonstrate width reduction of the pipeline RoW as it passes through a wetland; note the channels created to reduce sedimentation and erosion; in (b) red line denotes the pipeline; (c), (d) and (e) demonstrate micro-routing and width reduction of the pipeline RoW as it passes through additional habitats; and, (f) illustrates side casting which minimizes habitat impact and erosion and allows for vegetation restoration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Biodiversity and ecosystem services values (BES) assigned to each major habitat classification. These values are estimated for this study and do not represent universal values.

Habitat	Assigned BES significance for this study
Andean wetlands and peat-bogs	5
Native forest (Upper montane forest and dry forest)	5
Scrublands/scrub (montane/thorny/resinous/mixed)	4
Cactus/desert scrub habitat	4
Native grasslands (sward and tussock)	3
Dune vegetation (*Tillandsia* spp.)	4
Scarce or no vegetation/no priority species identified	1

quantitative tool used for our analysis. For example, wetlands and all aquatic habitats were assigned a BES of five due to ecosystem services provided (such as habitat for native species, carbon sequestration and support of hydrological systems), importance expressed by local communities in pre-construction workshops and biodiversity value, as were native forest habitats (Walsh Peru 2005). Scrublands were assigned a value of four, because although they are habitat for endemic species of birds and reptiles (Domus Consultoria Ambiental 2007) and are sensitive from a biodiversity standpoint, these habitats were not considered a priority by local communities (Walsh Peru 2005). Native grasslands were assigned a BES level of three because while they are important for livestock grazing and assigned a high sensitivity value for this reason (Walsh Peru 2005), they are widespread, and had fewer endemic animal species identified as compared to other habitats (Domus Consultoria Ambiental 2007). Cactus communities in desert scrub habitat were assigned a value of four because while some species are endangered and endemic (Domus Consultoria Ambiental 2007), few direct social impacts or concerns were noted during the ESIA process. Areas with scarce to no vegetation that did not contain priority species were assigned a BES value of one. Our BES values, therefore, are estimates based on ESIA and surveys specific to this project and do not represent universal values for habitats and species. We calculated quality hectares using the area of affected habitat multiplied by its assigned BES value and its quality value. Habitats in control areas and in areas of the RoW prior to construction were assigned a quality value of one, while habitats impacted by the RoW were assigned a quality value equivalent to its degree of restoration based on plant diversity and vegetation cover (i.e. a value less than one).

We did not include BES values for rivers and streams in our analysis because of the difficulty of assessing an area of impact to them. Data from the BMAP, however, determined that no biodiversity impacts could be detected due to the RoW crossing streams (Alonso et al. 2013).

We designated a spatial impact scale value of zero if no impact was detected within or outside of the RoW, scale value of one to areas where biodiversity and vegetation cover was affected at a local scale (within 10 m). Our scale included a potential impact scale value of two if the impact was wider in scale (> 10 m < 1000 m) with a demonstrated reduction in biodiversity or vegetation cover at a regional scale. We found all impacts to be site-specific and limited to the RoW (Alonso et al. 2013) and therefore they were assigned an impact scale value of one.

3.3. Monitoring vegetation restoration

Impacts related to site-based recovery of biodiversity on a temporal scale were tracked yearly through the vegetation monitoring and the BMAP site- and species-species specific protocols. We used point-line transect data from ELUs 1–11 (241 km) assessed annually, from 2010 to 2014, by the company's bio-restoration program. We evaluated one hundred points for each 500 m section of the RoW on ELUs 1–11, determining plant species composition within a one inch diameter ring as well as relative vegetation cover for each 100 points. Two transects were evaluated inside the RoW per kilometer and two transects 10–50 m outside the RoW as control sites. Plant species composition and vegetation cover inside the RoW relative to control sites were utilized for assessing habitat quality.

3.4. Quantifying avoidance in quality hectares

We used satellite images data entered in ArcGIS to calculate the area of habitat polygons present on the RoW along the pipeline route (Fig. 4b). We then used vegetation cover data to determine a measure of the habitat type in quality hectares for both the original route and the final route. We used a GIS model to calculate the habitat not impacted and habitat impacted due to micro-routing and route width minimization. We used the original pipeline route with a 12.5 m buffer to generate the quality hectares of potential impact of the RoW. We used the same method to determine the quality hectares avoided (route with micro-routing to avoid sensitive habitats) for the final route.

Once we obtained the data of habitat potentially impacted by the original ROW, the quality hectares reduced through micro-routing and width minimization for the revised route, and data on restoration of vegetation for ELU's 1–11 from 2010 to 2014, we calculated remaining impacts. For ELU's 12–14, where restoration monitoring did not regularly occur, we calculated impacts based on avoidance and width minimization actions only.

Our estimate of impacts was calculated using quality hectares; however, unlike projects that compare habitat quality in the project area to an offset area (The Biodiversity Consultancy and Fauna and Flora International 2012b), we compared impacted areas to control sites, which served as a baseline for monitoring. We first multiplied habitat area to be impacted by RoW construction by its BES value, which provided each habitat with a priority value. Because the quality of the habitat is compared to non-impacted, control sites (assigned a quality value of 1), all habitats were assigned a value of 1 prior to construction. After RoW construction, habitat quality was assessed by comparing vegetation abundance and diversity inside the RoW to vegetation abundance and diversity in control plots via a restoration index (see below). Our residual impact calculations therefore, take into account the quality hectares of habitat impacted (at time of construction) and the reduction in impacts over time due to restoration activities.

3.5. Calculation of impacts due to construction of the RoW

We used the following formulas (impact values in quality hectares) to calculate:

Impact of the original route ($ARoW_o$)

Area of original RoW (25 m) $*$ Impact scale value $*$ BES value of habitat $*$ Quality (value of 1).

Impact avoided with micro-routing ($ARoW_a$)

Area of original RoW avoided with micro-routing $*$ Impact scale value $*$ BES value of habitat $*$ Quality (value of 1).

Minimized impact ($ARoW_m$)

Area of original RoW with width minimization $*$ Impact scale value $*$ BES value of habitat $*$ Quality (value of 1).

Restoration index (quality value post-construction) (Q_{Ri})

$$Q_{Ri(n)} = 1 - \{(RoWnvc/C\ nvc) + (RoWnsr/C\ nsr)\}/2$$

Where:

RoW nvc	proportion of native vegetation cover in RoW sample
C nvc	proportion of native vegetation cover in Control sample
RoW nsr	native species richness in RoW sample
C nsr	native species richness in Control sample.

The formula to determine residual impact in quality hectares for the PERU LNG RoW for each year was therefore:

$$\text{Residual impact}_n = [\,(\textstyle\sum ARoW_o{}^{*}\ IS^{*}\ BES^{*}\ Q) - \{\,(\textstyle\sum ARoW_a{}^{*}\ IS^{*}\ BES^{*}\ Q)\,Q_{Ri(n)} + (\textstyle\sum ARoW_m{}^{*}\ IS^{*}\ BES^{*}\ Q)\,\}\,]^{*}$$

Where:

IS	Impact scale value
BES	BES significance
Q	Quality value (value of 1 for habitats prior to impact)
$ARoW_o$	Area of Original RoW (before construction)
$ARoW_a$	Areas added or avoided due to habitat prioritization by micro-routing (during construction)
$ARoW_m$	Area further avoided by width minimization (during construction)
Q_{Ri}	Restoration index (serves as quality measure post-construction)
n	Year.

We calculated a restoration index for each 500 m section along the RoW for ELUs 1–11 for each year of monitoring. To examine restoration trajectories, we calculated correlation coefficients between restoration indices and year for habitats in ELU's combined.

3.6. Site specific monitoring through the Biodiversity Monitoring and Assessment Program (BMAP): small rodents in montane forest

ELU 1 of the RoW contains montane rainforest which was assigned a BES value of five since it was designated as a sensitive habitat in the ESIA (Walsh Peru 2005). Soon after pipeline construction, small rodent populations were monitored via live-capture and marking. Pacheco et al. (2013) and Salas et al. (2013) did not find differences in the abundance and diversity of the small rodents in the RoW as compared to nearby control sites. As the RoW recovered its vegetation, the monitoring protocol incorporated rodent diet and found the community of rodents to be seed dispersers (Sahley et al. 2015, 2016) demonstrating their importance to ecosystem health.

Table 2

Potential impact of original route, avoidance of habitats, minimization of route width, restoration value and residual impacts for ELU's and major habitat types found within the pipeline. Units are in in quality hectares (Qha), which are the number of hectares of habitat within the RoW multiplied by the BES value of the habitat and its quality. Quality is 1 for habitats at time of construction (during micro-routing and width minimization) and quality is equal to restoration index value after construction (restoration and residual impact). Negative values correspond to habitats and ELU's where impacts increased.

Ecological landscape unit	Habitat	Potential impact with original route		Avoidance via micro-routing		Minimization		Restoration value		Residual impact	
		Qha	%	Qha	%	Qha	%	Qha	%	Qha	%
1-Apurimac River Valley Montane Forest Ecotone	Entire ELU	129.5	100.0	11.9	9.2	10.7	8.3	65.3	50.4	41.6	32.1
	Montane forest	3.36	2.6	0.27	8.02	2.85	84.83	0.12	3.63	0.12	3.53
	Wetland	1.72	1.3	0.15	8.90	0.44	25.39	0.00	0.00	1.13	65.71
	Grassland	61.96	47.8	2.38	3.84	1.62	2.62	34.79	56.15	23.16	37.39
	Montane scrub	61.61	47.6	9.25	15.01	4.93	7.99	30.28	49.15	17.15	27.84
2-Campana Watershed	Entire ELU	20.1	100.0	− 6.1	− 30.5	0.7	3.5	13.2	65.6	10.9	54.1
	Grassland	16.37	81.4	− 5.65	− 34.54	0.23	1.40	13.20	80.67	8.59	52.47
	Thorny scrub	0.67	3.3	0.23	35.10	0.43	64.90	0.00	0.00	0.00	0.00
	Wetlands	2.79	13.9	− 0.67	− 24.14	1.17	41.82	0.00	0.00	2.30	82.32
3-Torobamba River Valley	Entire ELU	77.3	100.0	− 2.6	− 3.4	9.6	12.4	61.9	80.1	8.5	11.0
	Dry Forest	5.72	7.4	3.22	56.30	2.50	43.70	0.00	0.00	0.00	0.00
	Thorny Scrub	44.06	57.0	− 6.30	− 14.29	5.54	12.58	42.30	96.00	2.51	5.71
	Grassland	26.94	34.9	0.75	2.78	0.67	2.47	19.58	72.67	5.95	22.08
4-Sillaccasa Sierra	Entire ELU	94.1	100.0	− 0.3	− 0.3	4.3	4.5	65.7	69.8	24.5	26.0
	Grassland	89.92	95.5	− 0.53	− 0.59	3.44	3.83	64.73	71.98	22.29	24.79
	Thorny Scrub	2.24	2.4	− 0.05	− 2.07	0.19	8.59	0.98	43.49	1.12	49.98
	Wetlands	1.83	1.9	0.26	14.43	0.51	27.67	0.00	0.00	1.06	57.90
5-Yucay River Valley	Entire ELU	30.1	100.0	6.1	20.2	2.0	6.6	11.7	38.8	10.3	34.3
	Thorny Scrub	23.66	78.6	4.84	20.45	1.78	7.51	9.75	41.23	7.29	30.82
	Grassland	4.33	14.4	1.06	24.40	0.16	3.61	1.78	41.18	1.33	30.81
	Wetland	1.79	5.9	0.03	1.70	0.05	2.79	0.00	0.00	1.71	95.51
6-Huamanga Vischongo Watershed Divide	Entire ELU	218.4	100.0	− 2.9	− 1.3	9.6	4.4	162.5	74.4	49.1	22.5
	Grassland	212.67	97.4	− 3.03	− 1.43	7.07	3.32	162.19	76.26	46.45	21.84
	Wetland	5.26	2.4	0.21	4.01	2.43	46.07	0.00	0.00	2.63	49.93
7-Vinchos River Valley	Entire ELU	51.5	100.0	− 3.0	− 5.8	4.0	7.8	32.3	62.8	18.1	35.2
	Grassland	46.90	91.1	− 3.08	− 6.57	1.87	3.99	30.58	65.20	17.53	37.38
	Scrub	3.96	7.7	0.48	12.09	2.09	52.82	0.81	20.50	0.58	14.59
8-Apacheta High Sierras	Entire ELU	293.5	100.0	5.2	1.8	19.4	6.6	146.5	49.9	122.4	41.7
	Grassland	242.24	82.5	1.90	0.79	10.32	4.26	132.93	54.88	97.09	40.08
	Peat bogs	28.23	9.6	4.70	16.64	7.75	27.46	1.16	4.11	14.62	51.79
	Scarce vegetation	22.89	7.8	− 1.37	− 5.97	1.30	5.67	12.28	53.64	10.68	46.66
9-Pampas Palmitos Basin	Entire ELU	220.4	100.0	1.4	0.7	20.2	9.2	114.1	51.8	84.7	38.4
	Grassland	186.47	84.6	− 1.2	− 0.64	15.8	8.49	105.0	56.29	66.9	35.86
	Wetlands	5.17	2.3	1.9	37.64	2.8	53.50	0.00	0.00	6.91	133.63
	Peat-Bogs	11.63	5.3	1.6	13.45	0.9	7.69	0.0	0.00	2.7	23.35
	Scarce vegetation	15.60	7.1	− 0.3	− 1.96	0.3	1.98	7.9	50.66	8.2	52.71
10-Huaytara High Plains and Ridges	Entire ELU	439.0	100.0	− 1.2	− 0.3	32.0	7.3	254.5	58.0	153.8	35.0
	Grasslands	253.77	57.8	5.52	2.17	29.82	11.75	125.24	49.35	93.20	36.72
	Mixed scrub	166.90	38.0	− 9.32	− 5.58	0.26	0.16	122.86	73.62	53.09	31.81
	Peat bogs	8.48	1.9	2.57	30.23	1.74	20.48	0.00	0.00	4.18	49.28
	Scarce vegetation	6.93	1.6	0.03	0.42	0.13	1.86	3.48	50.25	3.29	47.47
11-Pisco-Ica Watershed Divide	Entire ELU	207.6	100.0	− 13.5	− 6.5	8.9	4.3	153.8	74.1	58.4	28.1
	Mixed scrub	186.44	89.8	− 27.75	− 14.89	8.38	4.49	151.13	81.06	54.7	29.33
	Grasslands	16.71	8.0	11.08	66.32	0.52	3.11	1.86	11.13	3.2	19.44
	Scarce Vegetation	4.26	2.1	3.16	74.30	0.04	0.91	0.64	15.02	0.4	9.77
12-Coastal Bat Hills	Entire ELU	203.1	100.0	− 1.2	− 0.6	21.5	10.6	0.1	0.0	182.8	90.0
	Desert Scrub	146.58	72.2	0.03	0.02	15.67	10.69	0.00	0.00	130.88	89.29
	Scarce Vegetation	50.12	24.7	0.13	0.26	1.05	2.09	0.00	0.00	48.94	97.64
	Columnar cacti	2.59	1.3	− 1.96	− 75.53	4.55	175.53	0.00	0.00	0.00	0.00
	Grassland	1.34	0.7	− 0.83	− 61.56	0.20	15.03	0.00	0.00	1.97	146.53
13-Pisco Sand Plains	Entire ELU	69.6	100.0	5.1	7.4	3.0	4.3	61.4	88.3	0.0	0.0
	Dune vegetation/ Tillandsia spp.	9.62	13.8	6.8	70.67	2.8	29.33	0.0	0.00	0.0	0.00
	Scarce vegetation/No vegetation	59.29	85.2	− 2.0	− 3.31	0.1	0.17	61.1	103.14	0.0	0.00
14-Ica-Lima Coastal Plain	Entire ELU	119.3	100.0	− 11.1	− 9.3	12.2	10.3	118.2	99.0	0.0	0.0
	Dune vegetation/ Tillandsia spp.	1.33	1.1	− 1.03	− 77.10	2.36	177.10	0.0	0.00	0.0	0.00
	Scarce vegetation/No vegetation	117.57	98.5	− 10.02	− 8.52	9.43	8.02	118.1	100.43	0.0	0.00

*Yearly monitoring not conducted so restoration values are not available. (Site specific monitoring protocols for wetlands directly crossed by the RoW were developed in 2013 and not included in this analysis).

**Residual impacts are based on 2010 values due to lack of yearly restoration data.

***Residual impacts from tree removal in ELU 3 are < 0.02 ha and not measurable via satellite imagery.

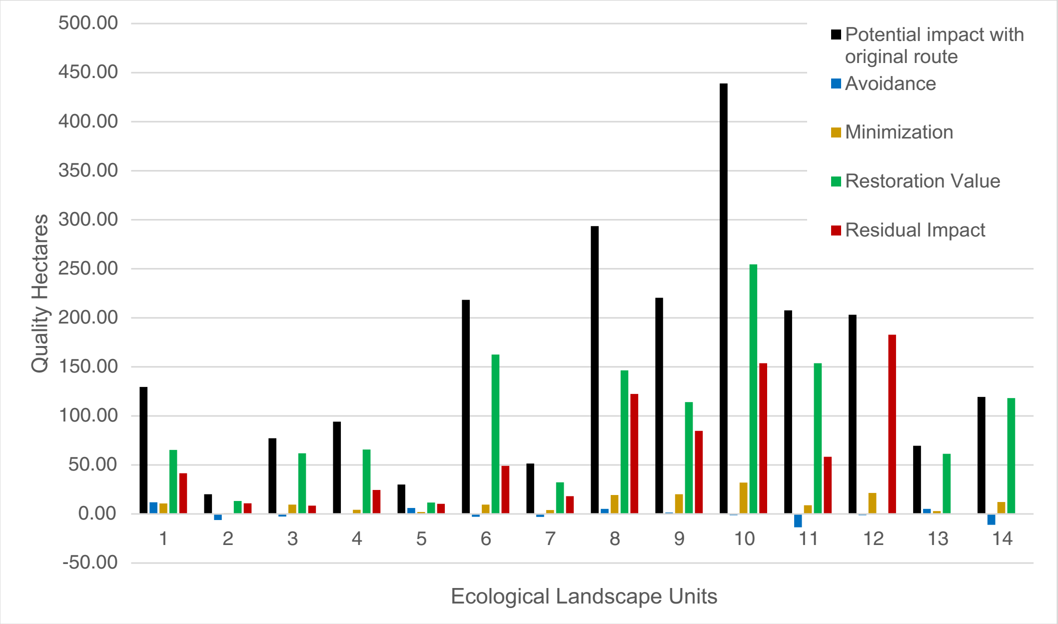

Fig. 5. Reduction in impacts to the original pipeline (2010) achieved through application of the mitigation hierarchy (2014).

4. Results

4.1. Summary of mitigation hierarchy efforts by Ecological Landscape Unit (ELU)

We found that application of the mitigation hierarchy to the pipeline RoW during construction and post-construction led to a substantial reduction in residual impacts for all ELU's (Table 2). We found that restoration resulted in the greatest reduction of residual impacts in the optimum pipeline corridor, followed by avoidance via micro-routing in combination with RoW width minimization (Fig. 5). Avoidance of priority habitats could entail additional impacts in lower priority habitats. We found that residual impacts were largest in ELUs 8, 9, and 10, primarily composed of grassland habitats located at high altitudes with low rainfall regimes and where cold temperatures (below freezing point) are frequent. The eastern Andean ELUs (primarily forest and scrub habitat) had considerably fewer residual impacts. The Pacific Watershed ELUs, which were not subject to a restoration program, had few residual impacts with the exception of ELU 12 (primarily desert/cactus scrub).

4.2. Avoidance via micro-routing and width reduction of the RoW

Micro-routing adjustments made during construction of the pipeline RoW led to a proportionally greater avoidance of high BES habitats such as montane forest, dry forest, montane shrub and Andean wetland as compared to medium BES habitat such as grassland (Table 2). Avoidance through micro-routing (done for purposes of avoiding priority habitats, villages, and archeological remains) slightly increased impacts on some natural habitats for 7 out of 10 ELU's (ELU's 2, 3, 6, 7, 8, 11, 14). These habitats were grasslands (BES value of 3, 7/16 cases), areas of scarce vegetation (BES value of 1, 4/16 cases), scrub vegetation (BES value of 4, 5/16 cases), vegetation dominated by columnar cacti (BES value of 4, 1/16 cases) and in one case a small increase occurred in a wetland (BES value of 5, 1/16 cases). Thus, avoidance of priority habitats can lead to greater impacts in lower priority habitats. Width reduction of the RoW lessened impacts in all ELU's and habitats, so that the combination of avoidance and width reduction (actual footprint) resulted in a reduction of impacts. When habitat types are combined irrespective of ELU, high BES habitats such as dry and upper montane forests as well as *Tillandsia* vegetation have high avoidance values and correspondingly zero to small amounts of residual habitat by area, even though for dry forest and montane forest, trees located directly in the RoW were removed (42 and 25 trees, respectively). Replanting of these trees within the RoW is not feasible, due to pipeline integrity needs. BMAP personnel (see below) are collecting data to evaluate and offer guidance on how to minimize impacts via restoration. Grassland had the lowest avoidance and width minimization values. Residual impacts, as measured by vegetation cover and plant species diversity range, from zero or near zero for *Tillandsia* vegetation, dry forest vegetation, and montane forest to more intermediate values for scrubland, wetland, upper montane scrub, and grassland. Desert-cactus scrub had the highest level of residual impacts even with comparable values for avoidance and width minimization.

4.3. Vegetation restoration

Vegetation restoration contributed the most to decreasing residual impacts in the RoW. A restoration index based on vegetation cover and species richness within the RoW as compared to outside the RoW, indicated a positive and significant correlation between 2010 and 2014 (Fig. 6; $\rho = 0.649$, $n = 209$, $P < 0.001$). Positive correlation coefficients between 2010 and 2014 were found for ELUs 1, 2, 3, 4, 6, 7, 8, and 11. For ELU's 5 and 9, which are primarily Andean grasslands, significant negative correlations were found. For ELU 10, also comprised mainly of high altitude grassland, neither a positive nor negative correlation was found (Table 3).

4.4. BMAP: site-specific and species monitoring at ELU 1 Apurimac river montane forest ecotone

Alonso et al. (2013) documented results for all site- and species-specific BMAP protocols implemented during and after pipeline construction. Here we present data for ELU 1, the Apurimac River Valley Montane forest ecotone, to demonstrate how site- and species-specific, hypothesis driven monitoring complements the yearly point-transect vegetation monitoring carried on by the company to inform restoration status and trends. ELU 1 is characterized by a high elevation montane forest that transitions into high Andean grassland habitat. It contains high elevation montane forests, montane scrub habitat (both

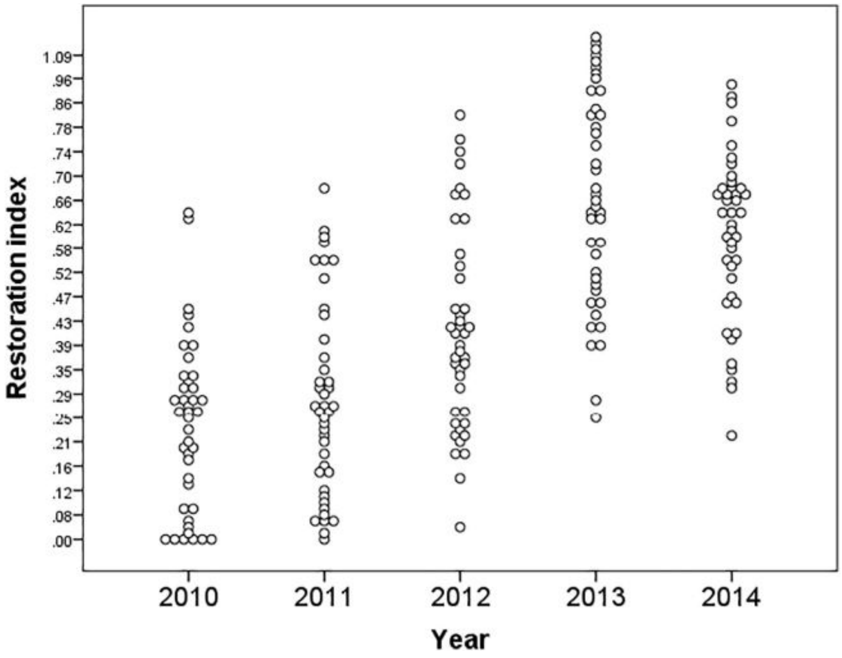

Fig. 6. Scatterplot for restoration indices for all ELU's combined for 2010–2014. The restoration index is significantly and positively correlated with year. This indicates that if present trends continue, residual impacts will continue to decrease.

Table 3
Correlation coefficients and *P* values for Ecological landscape units 1–11.

Ecological Landscape Unit (ELU)	Number of samples (n)	Correlation coefficient (ρ)	*P* value
1-Apurimac River Valley Montane Forest Ecotone	209	0.616	$P < 0.01$
2-Campana Watershed	50	0.643	$P < 0.001$
3-Torobamba River Valley	200	0.451	$P < 0.001$
4-Sillaccasa Sierra	126	0.356	$P < 0.001$
5-Yucay River Valley	146	− 0.185	$P < 0.05$
6-Huamanga-Vischongo	298	0.652	$P < 0.001$
7-Vinchos River Valley	134	0.326	$P < 0.005$
8-Apacheta High Sierras	420	0.196	$P < 0.001$
9-Pampas Palmitos Basin	238	− 0.192	$P < 0.001$
10-Huaytara High Plains and Ridges	542	0.004	$P = 0.917$
11-Pisco-Ica Watershed Divide	210	0.416	$P = 0.001$

comprising 24% of the RoW), tussock and sward forming grasslands, and one wetland (Domus Consultoria Ambiental 2007, Langstroth et al. 2013).

While total number of hectares of upper montane forest was relatively small in the RoW construction area, this habitat was identified as highly sensitive in the ESIA (Walsh Peru 2005). The Ecological Field Survey (Domus Consultoria Ambiental 2007) and subsequent BMAP research protocols confirmed the presence of endemic species of birds and small mammals, as well as a high diversity of plant species (Pacheco et al. 2013, Servat et al. 2013, Salas et al. 2013). Impacts during RoW construction on lizards were not detected (Gutierrez et al. 2013), and negative impacts on rodent abundance and diversity were not found (Pacheco et al. 2013, Salas et al. 2013). However, due to pipeline construction a reduction in utilization of the RoW by rodents and subsequent rodent-mediated seed dispersal was detected (Fig. 7; Sahley et al. 2016).

Based on these findings, the BMAP adapted the rodent community monitoring program to include diet and seed dispersal studies (Sahley et al. 2015, 2016). Plant species that produced fruits that rodents were consuming were grown in nurseries and then planted in the RoW to restore connectivity and promote seed dispersal services in the RoW which, in turn, increased small mammal utilization of the RoW, enhanced ecosystem function and biodiversity recovery (Pacheco et al. 2013, Sahley et al. 2015, 2016, Servat et al. 2013; Fig.8).

This information was used to guide shrub re-planting efforts. For example, in 2014, two shrub species utilized by rodents were planted in three different corridor designs in order to facilitate rodents crossing the RoW. Site-specific monitoring protocols were adaptively adjusted to monitor improvements in landscape connectivity and also provide additional data to set targets that measure restoration success, such as habitat connectivity and effective seed dispersal.

5. Discussion

In this study we quantified avoidance, minimization, restoration, and residual impacts of the mitigation hierarchy for a natural gas pipeline RoW located in the tropical Andes. We found that avoidance combined with width minimization of the RoW contributed to reducing impacts in all ELU's. High BES value habitats especially benefitted, and in most cases, restoration further reduced residual impacts over time resulting in a positive restoration trajectory along most of the RoW. Measuring restoration was crucial as it is a response variable that allows assessment of the effectiveness of mitigation measures as well as specific restoration activities. Biodiversity impacts were limited to the pipeline RoW (Alonso et al. 2013) similar to findings of Jones et al. (2014) who documented impacts limited to areas of the physical infrastructure of a natural gas pipeline in Uzbekistan.

The vegetation restoration program combined with a site-specific and hypothesis-driven BMAP was used in an adaptive management framework to inform and guide yearly company restoration efforts. These efforts measured impact on species as well as components of ecosystem health and function such as seed dispersal (Sahley et al. 2016) that were not measured by analysis of satellite imagery or vegetation surveys. Current restoration efforts at the site have incorporated restoration of connectivity as a target with rodent utilization of the RoW being an important indicator. This is an example where original site monitoring protocols emphasizing diversity and abundance of species have been adjusted to include additional components based on research results. Restoration efforts are currently ongoing as residual impacts continue to decrease.

The spatial scale vegetation monitoring (point-transect monitoring for ELU's 1–11) on a yearly basis provided information on restoration trends. It allowed us to estimate residual impacts on a yearly basis for

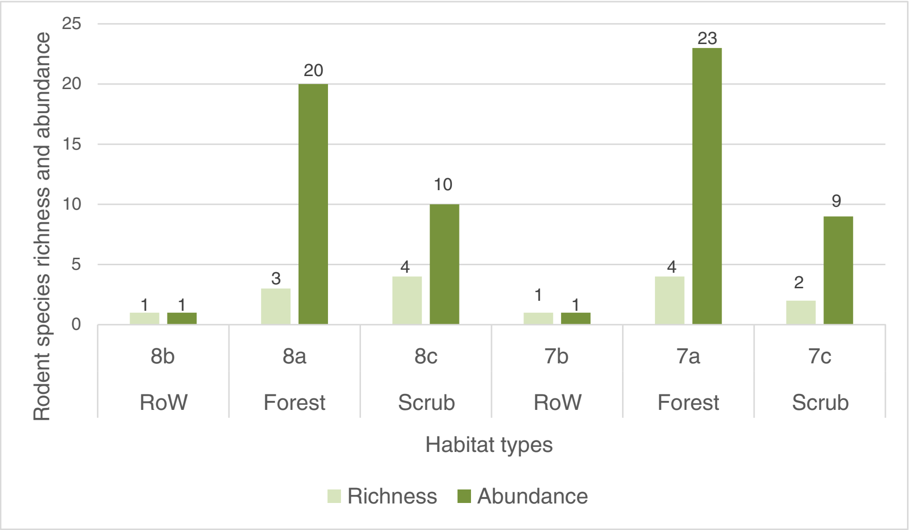

Fig. 7. Rodent utilization of the RoW in 2012 as compared to forest and shrub habitat on both sides of the pipeline in two study sites. Use of the RoW in 2012 was limited, as only one capture with one species (*Calomys sorellus*) occurred in each site.

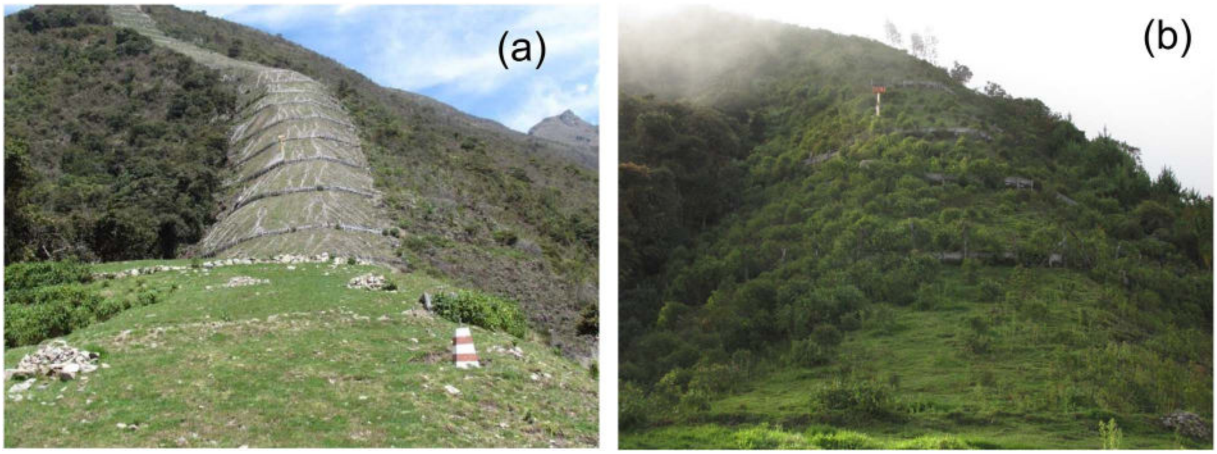

Fig. 8. Montane forest habitat at Kilometer progressive 1 in May 2011 (a) and February 2015 after restoration efforts (b). Rodent utilization of the RoW is being monitored in 2016 and 2017 to determine whether habitat connectivity has been re-established.

most habitats, which generated the data driven information to plan and implement timely restoration. Monitoring of vegetation in control plots allows us to compare impacted plots with a non-static baseline and provides information to reach target values similar to those found at control sites. Continued monitoring coupled with forecasting techniques can be used to calculate when restoration trends might reach targeted values. The site-specific, statistically-validated monitoring of plant and animal communities and species within the RoW after construction, coupled with indicators of ecosystem function such as seed dispersal and presence of insectivore lizards in the RoW, was important in guiding restoration efforts. The specific goals for the restoration of various habitats included comparable plant diversity and plant cover in all habitats as well as additional components of ecosystem function, and utilization by scale-appropriate indicator species for each habitat such as lizards and rodents. Yearly surveys of plant diversity and cover with respect to control plots allowed us to estimate a rate of recovery. More detailed, site specific BMAP protocols allowed us to understand restoration processes such as plant and animal recolonization, which cannot be measured through habitat area-only assessments and provide information to facilitate restoration.

Several factors contributed to the successful implementation and quantification of the mitigation hierarchy. The design of a biodiversity action plan (PERU LNG 2007a) prior to construction of the pipeline provided the roadmap for the implementation of the project strategies and actions to protect biodiversity and ecosystem services. The BAP incorporated the mitigation hierarchy as a fundamental part of its design and steps to avoid, minimize and restore habitats were outlined and documented during all phases of the project (Dallmeier et al. 2013, Taborga and Casaretto 2013). The BMAP was designed to answer management questions and is structured in data-driven research and monitoring protocols that generated the information needed for the planning and implementation of restoration activities (Dallmeier et al. 2013). It provided a second roadmap to periodically monitor indicator species and habitats regularly, in the area of impact of the RoW during project construction and post-construction, within the RoW itself (Alonso et al. 2013). A database was created for all aspects of the BMAP that included data from satellite images, GIS, habitat and species monitoring. It facilitated the calculation of the restoration outcome trends and the residual impacts on a yearly basis, and allowed the company to prioritize restoration efforts.

Limitations to the approach presented here included lack of knowledge on priority species and habitats. This hampered our ability to quantitatively predict impacts prior to construction of the RoW. Although a BAP and the mitigation hierarchy were implemented prior to and after construction, quantitative prediction of impacts was not included in the ESIA, which was carried out according to Peruvian environmental law. The dearth of knowledge also makes restoration a challenge, especially at altitudes above 4000 m and in extremely arid habitats. These knowledge gaps emphasize the importance of establishing monitoring programs that not only quantify species diversity and abundance in the area of the project, but that also investigate ecological processes important to habitat recovery. We suggest that prior to project start-up, that BAPs or ESIAs include impact predictions on species, habitats and ecological services that can be used to guide the development of monitoring and restoration protocols. Where information on these is absent, monitoring protocols should include basic research to estimate quantification of impact predictions as soon as the project permits.

While we documented temporal losses in biodiversity, the monitoring program established that these were limited to the 25 m RoW and did not significantly impact species and habitats outside of the direct pipeline construction footprint. However, our analysis did not include assessing access routes from the main highway to areas of the pipeline RoW. We recommend that monitoring programs consider the spatial scale of impacts during project conception and adjust their monitoring protocols accordingly. We did find that lack of connectivity hampered rodent utilization of the RoW in montane rain forest and potentially could hamper seed dispersal over a larger area than the RoW; current restoration efforts are addressing this question.

As discussion continues about how to apply and quantify the mitigation hierarchy in order to reduce project residual impacts, facilitate offset planning when appropriate and ultimately determine recovery trajectories to established targets, it is important that mega-infrastructure projects that require best practices to protect and manage biodiversity apply methods to document and quantify the application of the mitigation hierarchy. This can inform project management decisions, guide restoration efforts, and assist with measuring overall impact as well as assist with project offset and conservation actions (Cross Sector Biodiversity Initiative, 2015). In addition to planning and implementing of avoidance and minimization activities via robust, detailed, and documented biodiversity action plans, biodiversity monitoring protocols are essential for obtaining measurable information over time to determine restoration trends and calculating residual impacts. A well designed monitoring program that incorporates hypothesis driven research questions on indicator species and communities provides reliable data and information for managing project impacts effectively while contributing to information and knowledge towards habitat restoration and species conservation. At our project site, restoration efforts continue to be guided by the monitoring program. When the mitigation hierarchy framework is integrated with project adaptive management, BMAP frameworks become the cornerstone for managing project environmental risk, especially in biodiversity sensitive areas.

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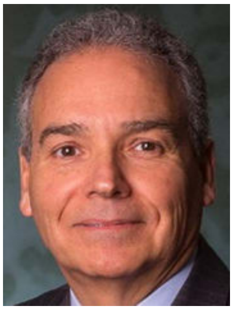

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