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RESEARCH ARTICLE

The effects of check dams and other erosion control structures on the restoration of Andean bofedal ecosystems

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Restoring degraded lands in rural environments that are heavily managed to meet subsistence needs is a challenge due to high rates of disturbance and resource extraction. This study investigates the efficacy of erosion control structures (ECSs) as restoration tools in the context of a watershed rehabilitation and wet meadow (*bofedal*) restoration program in the Bolivian Andes. In an effort to enhance water security and increase grazing stability, Aymara indigenous communities built over 15,000 check dams, 9,100 terraces, 5,300 infiltration ditches, and 35 pasture improvement trials. Communities built ECSs at different rates, and we compared vegetation change in the highest restoration management intensity, lowest restoration management intensity, and nonproject control communities. We used line transects to measure changes in vegetation cover and standing water in gullies with check dams and without check dams, and related these ground measurements to a time series (1986–2009) of normalized difference vegetation index derived from Landsat TM5 images. Evidence suggests that check dams increase bofedal vegetation and standing water at a local scale, and lead to increased greenness at a basin scale when combined with other ECSs. Watershed rehabilitation enhances ecosystem services significant to local communities (grazing stability, water security), which creates important synergies when conducting land restoration in rural development settings.

Key words: Aymara, human-environment system, indigenous people, land restoration, NDVI, wet meadow

Implications for Practice

- Check dams increase bofedal vegetation and standing water at a local scale but can also lead to landscape-level effects that extend beyond the surface area covered by check dams.
- The effects of large-scale and long-term restoration efforts need to be evaluated in the context of environmental change resulting from regional shifts in climate and land use.
- Check dams and other erosion control structures can increase grazing stability and water security for local communities. When land restoration is aligned with the provision of ecosystem services, indigenous people are capable of achieving extensive areas of land restoration even under continued agriculture and grazing management.

Introduction

Significant portions of the world's tropics have been degraded by human use, with land degradation concentrated in dryland montane areas managed by the rural poor (Bridges & Oldeman 1999; Lambin et al. 2003; Bai et al. 2008). Local and indigenous people can be effective at ecosystem restoration, provided there is sufficient social coordination and mobilization (e.g. Walters 2000; Long et al. 2003; Mingyi et al. 2003; Stringer et al. 2007; Blay et al. 2008). However, restoration efforts in rural environments that are heavily managed to meet subsistence needs are often complicated by high levels of disturbance from agriculture, grazing, fire, and biomass harvest (Brown & Lugo 1994; Lamb et al. 2005). To improve restoration success in rural development settings, there is a need to better understand restoration dynamics where land use pressure is high and management objectives include restoring ecosystem services important to local communities (e.g. grazing stability and water security).

A geographic region where intensive management by rural poor populations has led to environmental degradation is the Central Andes of South America (Ellenberg 1979; Sarmiento & Frolich 2002). The Central Andes are dominated by dry, tropical montane Puna grasslands composed of bunchgrasses, rosette-forming herbs, and dwarf shrubs in upland positions, and bofedal vegetation composed of rosette-forming herbs and cushion-forming species in seeps, springs, wet meadows, and floodplains (Squeo et al. 2006). Large portions of the Central

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Andes have been degraded due to population growth, changes in land management, and infrastructural development (Siebert 1983). Land degradation is characterized by reduced vegetative cover and productivity (Brandt & Townsend 2006), increased runoff and erosion (Harden 2001; Valentin et al. 2005), and deforestation of remnant *Polylepis* woodlands (Kessler 2002; Sarmiento & Frolich 2002).

Bofedales are particularly sensitive to changes in hydrology induced by gully erosion or prolonged drought (Earle et al. 2003; Moreau & Toan 2003; Squeo et al. 2006; Washington-Allen et al. 2008). Bofedal degradation impacts local livelihoods, as they are a vital source of dry season grazing for llamas and sheep. In the absence of active management, degraded bofedales may be slow to recover, remain suppressed at lower levels of productivity, or continue to degrade (Beisner et al. 2003; Scheffer & Carpenter 2003; Avni 2005). However, bofedales can be restored through watershed rehabilitation (Lal 1992; Valentin et al. 2005; Alemayehu et al. 2009). For example, erosion control and grazing management on slopes increases biomass, productivity, and infiltration (Trimble & Mendell 1995; Preston et al. 2002; Alemayehu et al. 2009; Mekuria & Veldkamp 2012). Check dams in gullies reduce water flow velocity and increase sediment deposition, soil moisture, and riparian vegetation (Boix-Fayos et al. 2008; Bombino et al. 2008; Zeng et al. 2009). Check dams and other grade control structures can also raise water tables to restore wet meadows incised by gullies (Shields et al. 1995; Schilling et al. 2003; Loheide & Gorelick 2007).

Although the local effects of erosion control structures (ECSs) are relatively well understood, their large-scale and long-term effectiveness have not been evaluated. This article investigates the efficacy of ECSs as restoration tools in the context of a watershed rehabilitation and bofedal restoration program in the Bolivian Andes. Specifically, we evaluate the effects of check dams, terraces, and infiltration ditches on bofedal vegetation and Puna grasslands in a rural development setting. We assess long-term and large-scale responses to watershed management using a combination of ground measurement (line transects to measure changes in vegetation) and remote sensing methods (a 1986–2009 time series of normalized difference vegetation index [NDVI] derived from Landsat TM5 satellite imagery).

Methods

Study Area

Geographic Setting. The study area is located in the Ayllu Majasaya-Aransaya-Urunsaya in the Tapacarí Province, Department of Cochabamba, Bolivia (Fig. 1). Ayllus are traditional Aymara indigenous territories with legal recognition in Bolivia. Situated along the Cochabamba-Oruro Highway on the Eastern Cordillera of the Andes, elevation ranges from 3,800 to 4,650 m. Mean annual precipitation is 400 mm/year, with 90% of the rain falling between November and March (Instituto Nacional de Estadisticas de Bolivia—Oruro Station 2012). Daily temperature fluctuations are high, with high solar insolation during the days (mean daily max = 19.2°C) alternating with cold nights (mean daily min = −0.17°C). Frosts generally occur in May and June. High winds, dust, and hypoxia are also components of this environment. Population densities are low (14.7 people/km^2), with people living in isolated ranchos. Land management is based on grazing sheep and llamas in Puna grasslands and bofedales, with agriculture conducted in the mesic valleys. Animals are grazed extensively and unfenced at an estimated 2.4 animals/ha when normalized to sheep livestock units, which exceeds the carrying capacity of 1.6 animals/ha (Alzerreca & Jerez 1989; Delgado Burgoa 2001).

Bofedal Degradation in the Study Area. Land degradation in the study area is set within a context of population growth, rural–urban migration, and land use changes resulting from land reforms in 1952. Gully erosion began on steep and marginal slopes that were converted to agriculture, and at culverts that discharged concentrated water flows along the main highway. Gullies widened over time and incised through alluvial valleys to form extensive drainage networks. Based on field observations and Google Earth® imagery, gullies are estimated to cover 10.2% of the land surface. Gullies on slopes are 2–10 m wide at the top-of-bank and up to 6-m deep, and can form ravines up to 40-m wide and 20-m deep when incised through alluvial valleys. Bofedales range from 0.25 to 12 ha and most have been incised by gullies.

Land degradation impacts bofedales in the study area through the following mechanisms: (1) reduced vegetative cover, increased runoff, and decreased infiltration rates on slopes reduce groundwater recharge, causing dry season water stress for wetland plants (Trimble & Mendell 1995; Salvador et al. 2014); (2) gullies that incise through bofedales lower water tables, changing species composition, also causing dry season water stress for wetland plants (Wright & Chambers 2002; Schilling et al. 2003; Loheide & Gorelick 2007; Loheide & Booth 2011); (3) increased flow velocities in channels can increase vegetation scour, leading to rapid development and destruction of bofedal vegetation in channels and floodplains (Earle et al. 2003); and (4) increased sediment transported from slopes can cover bofedales that are not incised by gullies, causing plant mortality, changes in species composition, and increased soil elevation relative to the water table (Werner & Zedler 2002; Miller et al. 2012).

Moisture gradients and grazing intensity drive bofedal species composition (Bosman et al. 1993; Ruthsatz 2012; Salvador et al. 2014). Cushion-forming species such as *Distichlis humilis* (Poaceae), *Plantago tubulosa* (Plantaginaceae), and *Ranunculus flagelliformis* (Ranunculaceae) are dominant in low-lying rivulets, pools, and saturated areas. In mesic hummocks and mounds, diminutive rosette species such as *Hypochoeris taraxicoides* (Asteraceae), *Hypsela reniformis* (Campanulaceae), and *Viola pygmaea* (Violaceae) become more common. If dry season water stress occurs due to erosion and sedimentation, grassland species such as *Festuca dolicophylla* (Poaceae), *Calamagrostis rigescens* (Poaceae), *Azorella biloba* (Apiaceae), and *Lachemilla pinnata* (Rosaceae) colonize the bofedales. Local people report that bofedales impacted

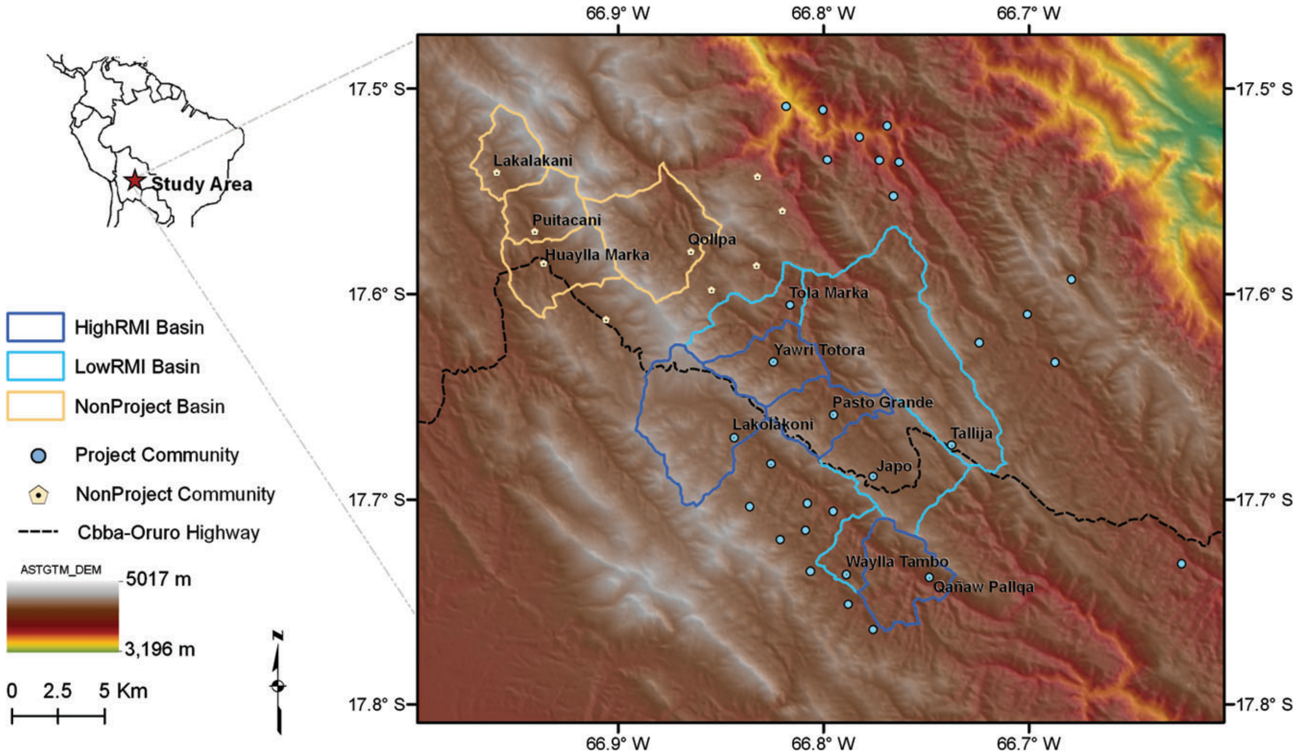

Figure 1. Location of the HighRMI, LowRMI, and NonProject control communities, watershed rehabilitation and wet meadow (bofedal) restoration project in the Ayllu Majasaya-Aransaya-Urunsaya. Study communities were selected after controlling for social and biophysical variables and based on restoration management intensity, defined as the density of erosion control structures/km^2.

by erosion and sedimentation support limited dry season grazing.

Watershed Rehabilitation and Wet Meadow Restoration Program. Land restoration efforts began in 1992 in a partnership between the Ayllu Majasaya-Aransaya-Urunsaya and a nongovernmental organization, the Dorothy Baker Environmental Studies Center (Centro de Estudios Ambientales Dorothy Baker, CEADB). The project eventually expanded to include over 30 communities and multiple resource management organizations. Local communities built over 30,000 ECSs as part of the watershed management program (Table 1). The majority of ECSs were built between 1996 and 2008. Community members typically built check dams in community work groups (*aines*). Work crews began building check dams at the headwaters along the main road and worked progressively down slope as gullies were consolidated. Efforts were later expanded to other areas and to other types of erosion controls (e.g. terraces and infiltration ditches on slopes) but the highest density of ECSs remained along the main road.

Study Basin Selection

There is a high degree of variability in the density of ECSs in project participant communities (from 14.7 to 225.3 ECSs/km^2, CEADB project records). Therefore, within the context of the watershed rehabilitation program at the Ayllu Majasaya-Aransaya-Urunsaya, restoration management intensity (RMI) was defined as:

$$\mathrm{RMI} = \text{No. erosion control structures/km}^2$$

We developed a sample design comparing the four highest restoration management intensity (HighRMI), four lowest restoration management intensity (LowRMI), and four non-project control communities (NonProject) (Table 2; Fig. 1). The HighRMI and LowRMI communities were identified from project participant communities after selecting communities within the Puna grassland vegetation zone (above 3,800 m) with similar geology, soils, and topography. Communities that began watershed rehabilitation after 2000 were excluded from consideration due to insufficient time for ecosystem development following physical interventions. HighRMI and LowRMI communities were part of the same system of social organization (the Ayllu), and adhered to similar agricultural production methods, grazing management practices, social institutions, and cultural norms and practices. The NonProject control communities were selected from a neighboring Ayllu along the same ridgeline as the project area, and also exhibited similar biophysical and social characteristics. However, control communities were not immediately adjacent to the study area and from a different Ayllu to reduce the potential for spatial auto-correlation and ensure independence of the NonProject communities from the HighRMI and LowRMI communities.

Table 1. Erosion control structures (ECSs) and other restoration methods used in the study area. The estimated numbers are from CEADB project records, and verified with community leaders.

Restoration Method	*Description*	*Estimated Number*
Check dam	A small dam constructed in a gully or drainage to reduce water flow velocity and trap sediment. Check dams can be constructed with a variety of materials (e.g. stones, logs, brush) but in the study area they are built exclusively with large stones. Check dams in the study are 1–4 m wide.	15,000 to 20,000
Terrace	A flat to gently sloping earthen platform built perpendicular to the slope to farm hilly or mountainous terrain. Terraces are typically constructed in a series of graduated steps to reduce runoff and erosion and increase soil nutrients and organic matter. In the study area, terraces are typically constructed with low stone walls 30–120 m long. Some slow-forming terraces are also built with earthen berms planted with grass to gradually trap sediment.	9,100
Infiltration ditch	A shallow trench dug perpendicular to the slope, designed to trap runoff and increase infiltration and groundwater recharge. Infiltration ditches in the study area are 30 cm wide and 20–40 m long, dug end-to-end in large fields.	5,300
Gabion	A gabion is a rectangular wire cage filled with rock or riprap. Gabions are lashed together and can be reinforced with concrete to build dams and trap sediment in larger ravines. Gabions require high material and labor investments to build, and are 5–20 m wide.	36
Pasture improvement trial	An exclosure designed to demonstrate the effect of reduced grazing on grasslands. One 5-ha pasture improvement trial constructed with barbed wire failed when the fence was not maintained, so community members built smaller 0.25–0.5 ha exclosures with durable rock walls.	35
Stock pond	Stock ponds are small excavated areas with constructed berms designed to provide stock water for grazing animals. Stock ponds are protected with barbed-wire fencing and gates, require heavy equipment to build, and are typically implemented with funding from municipal governments.	12
Tree planting	Due to the high elevations in the study area, *Polylepis incana* (keñua) and *Buddleia incana* (kiswara) planting was restricted to microclimates in ravines and in enclosures around ranchos below 4,200 m.	1,670

Community boundaries were equivalent to basin boundaries in the study area. Therefore, study basins were delineated for each community using a 30-m resolution ASTER Global DEM V2 downloaded from the NASA Land Process and Distributed Active Archive Center (LP DAAC). The DEM was reprojected to Universal Transverse Mercator (UTM) Zone 19S and the World Geodetic System 1984 (WGS-84) datum and ellipsoid, consistent with the Landsat TM5 images. Flow direction was determined and the drainage network was extracted based on a 0.1 km^2 flow accumulation threshold with standard GIS software. Watersheds were defined using outlet points, and the basin boundaries were delineated by merging polygons based on comparison with: (1) detailed sketch maps created by local communities (CEADB project records), (2) GPS points of key landmarks, and (3) ground-truthing with community informants in 2012. In general, the community boundaries followed ridgelines but in some cases a community boundary was defined by a river. In such cases, the polygons were clipped along the river centerline to create the community boundaries.

Line Transects

Line transects were established in five gullies with check dams and in five gullies without check dams to investigate potential changes in vegetation cover and to relate this information to NDVI. The sampling was designed to measure the effect of check dams on bofedal vegetation in the gully bottom and immediate banks, and control for potential variability due to aspect, slope, and whether the check dams were in the headwaters or further downstream. Gullies were selected at random after they were stratified, using the following rules. First, the headwaters had hillslope angles between 10 and 25° (based on field observation above 25° slopes water flow velocity is such that all vegetation is scoured from gullies even in cases where check dams are present, and below 10° slopes water velocity is low enough that bofedal vegetation cover is high, regardless of whether or not there are check dams). Second, the gully was located on the northeast side of the ridgeline along the Cochabamba-Oruro Highway rather than on southwest slopes (this reduced aspect related variability due to solar insolation and evapotranspiration rates). Twenty-eight gullies were surveyed on the northeast side of the Cochabamba-Oruro Highway, and of these 18 met the stratification rules (64.3%). From these five gullies with check dams and five gullies without check dams were randomly selected (Fig. 2). Once a gully was selected, the transect start point was randomly selected from 100 to 300 m below the confluence of the two feeder primary-order channels. The transects were placed in a second-order channel in the upper reaches of the drainage where the majority of check dams were constructed (this reduced variability from higher flow velocities from side channels that do not have check dams, and from higher water volumes in third- or fourth-order streams in lower reaches of the watershed). Line transects were established and measured at the end of the dry season in September. Line transects consisted of placing a 25-m tape measure down the center

Table 2. Characteristics of the study communities, watershed rehabilitation, and wet meadow (bofedal) restoration project in the Ayllu Majsaya-Aransaya-Urunsaya geographic region. Land tenancy refers to communities that allocated titled landholdings (average size = 40 has) or retain the communal landholdings (*ayanoka*). The number of families resident in each community is from a census conducted within the project area in 2006, and data not available for the NonProject communities. RMI, total number of erosion control structures (total ECSs) per km^2; Total ECSs, sum total of check dams, terraces, and infiltration ditches in each project community. RMI was not calculated for the NonProject communities as ECSs were not built.

			Location			*2006 Census*	*Erosion Control Structures (ECSs)*				
	Area (km^2)	*Elevation (m a.s.l.)*	*Latitude*	*Longitude*	*Land Tenancy*	*No. of families*	*Check dams*	*Terraces*	*Infiltration ditches*	*Total number of ECSs*	*RMI*$^{\gamma}$ *(ECS/km^2)*
HighRMI communities											
Lakolakoni	32.84	4,126–4,594	17°34′46″S	66°56′11″W	Private	81	3,400	2,600	1,400	7,400	225.3
Qañaw Pallqa	17.76	3,846–4,397	17°44′31″S	66°44′50″W	Communal	52	500	1,200	2,200	3,900	219.6
Yawri Totora	15.09	4,019–4,480	17°37′55″S	66°49′28″W	Private	71	1,200	1,100	900	3,200	212.1
Pasto Grande	14.41	4,027–4,480	17°39′32″S	66°47′40″W	Private	38	2,000	320	250	2,570	178.4
LowRMI Communities											
Waylla Tambo	7.21	3,934–4,384	17°44′10″S	66°47′26″W	Communal	38	300	120	110	530	73.5
Japo	28.84	4,074–4,390	17°41′45″S	66°45′50″W	Private	87	1,100	420	20	1,540	53.4
Tola Marka	14.58	3,986–4,595	17°36′22″S	66°49′00″W	Private	25	110	180	40	330	22.6
Tallija	63.32	3,821–4,430	17°40′45″S	66°43′49″W	Communal	129	580	320	30	930	14.7
NonProject Communities											
Huaylla Marka	17.49	4,028–4,574	17°35′07″S	66°56′11″W	Communal	—	—	—	—	—	—
Puitacani	12.57	4,074–4,654	17°34′10″S	66°56′27″W	Communal	—	—	—	—	—	—
Lakalakani	11.97	4,149–4,624	17°32′27″S	66°57′33″W	Communal	—	—	—	—	—	—
Qollpa	27.49	3,945–4,587	17°34′46″S	66°51′54″W	Communal	—	—	—	—	—	—

line of the gully, and a total of four 25-m line transects were laid end-to-end in each sample gully. Each 25-m section of the tape measure was laid out in a straight line that crossed representative topographic positions due to the natural gully meander, including the central thalweg, the gully bottom, and the portions of the immediate banks and side slope that encroached on the line. Meander was similar in gullies with check dams and without check dams. In cases where there was a severe bend in the gully, the trajectory of the tape measure was adjusted to follow the new gully direction by placing a metal pin in the center of the thalweg. The start and end point of each cover type (bofedal vegetation, Puna grassland, standing water, and bare areas) was measured in centimeter, and these values were converted to linear length and percent cover for each 25-m section ($n = 5 \times 4 \times 2 = 40$ measurements). The cover of different particle size classes in the bare areas was also noted as follows: bedrock, cobbles, gravel, and sand. The latitude–longitude location, channel depth, and channel width were recorded at the start and end points of each 25-m line transect. However, cross-sectional transect tapes were not placed to compare vegetation in the channel bottom with the top-of-bank. The contributing catchment areas of the five gullies with check dams and five gullies without check dams were calculated based on the flow accumulation at the downstream end of the sample area as calculated in GIS.

Remote Sensing Methods

A time series of Landsat TM5 images from 1986 to 2009 was constructed to evaluate long-term trends in NDVI. A total of 12 Landsat TM5 scenes were acquired for the study area. The images were acquired during the same time period in each sample year, on satellite overpasses between 12 May and 3 June. This period was selected in order to capture the dry-down immediately following the rainy season (November–April), as there was typically too much cloud cover during the rainy season for images to be useful. Only years with images free of clouds and haze in May and early June were included in the time series. Images were acquired from NASA LP DAAC and from the Brazilian National Institute for Space Research (INPE) receiving station. All images were projected to WGS-84 UTM Zone 19S and clipped to the study area boundary (upper left coordinate UTM zone 19S: 712425 E, 8073235 S; lower right coordinate UTM zone 19S: 764895 E, 8017705 S), and an image-to-image co-registration was performed using 28–100 automatically generated ground control points assisted by hand selected tie points. The resulting mean root mean square (RMS) error was 13.14 m, or about half the pixel size. The 1989 image was part of the USGS Global Land Survey (GLS); therefore, the Landsat TM5 images were well aligned with the DEM. Following the co-registration, all images were radiometrically calibrated with a dark object subtraction (Chavez 1988).

The NDVI values were calculated for each 30-m resolution pixel. NDVI is a vegetation index derived from remotely sensed data, and is a robust tool to measure relative changes in greenness that correlates well with biomass and productivity (Anderson et al. 1993; Lu et al. 2004). NDVI has been used as

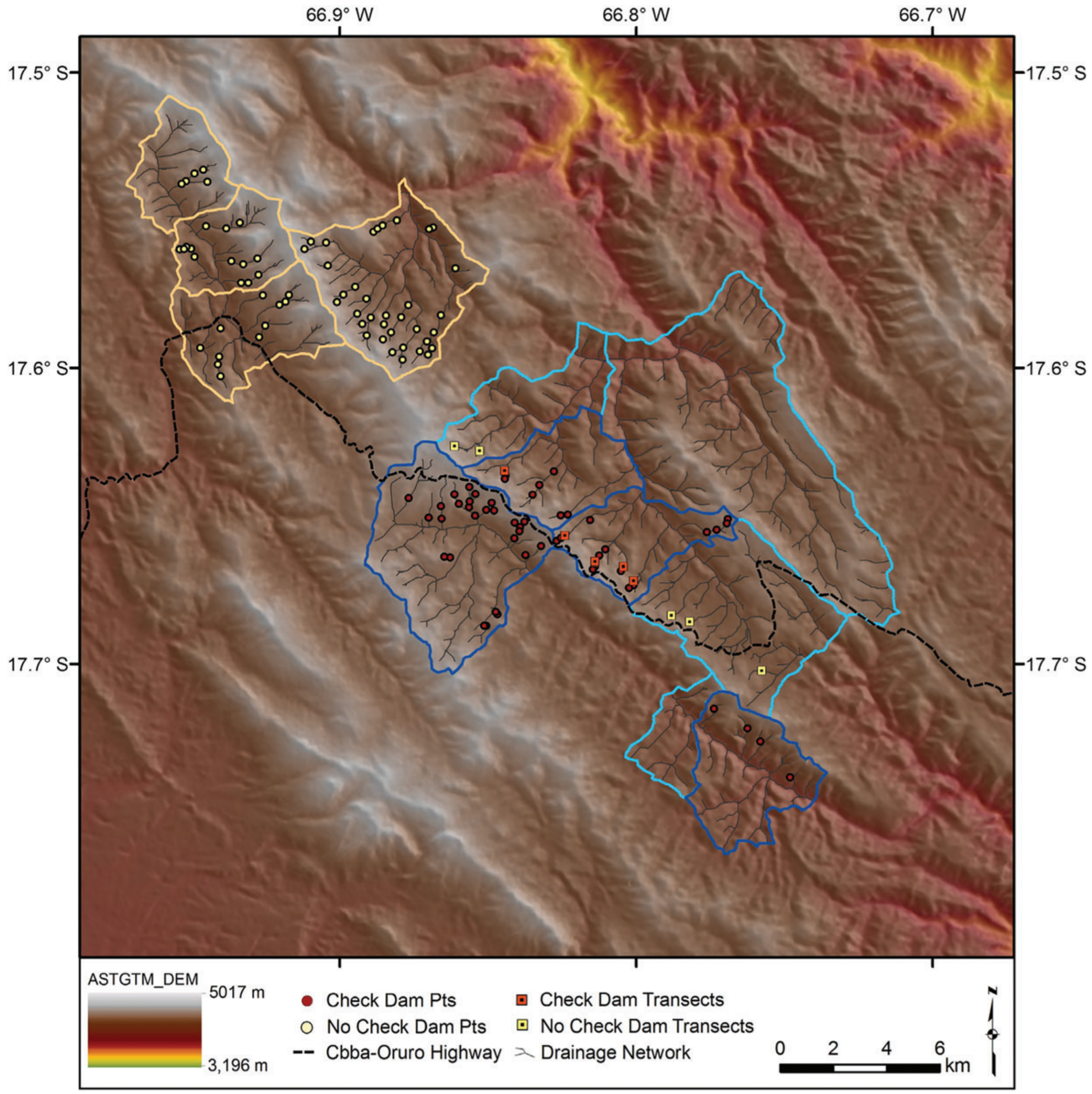

Figure 2. Location of the sample points in gullies with check dams ($n=52$) and in gullies without check dams in the nonproject area ($n=62$). Points were identified based on ground-truthing conducted in 2012 and from Google Earth® imagery taken on 8 August, 2009 and 10 August, 2010. The location of transects with check dams and without check dams is also included. Note that transects with check dams coincide with check dam points, so the markers for transects with check dams were purposely offset for clarity of presentation. The drainage network was modeled based on a 0.1 km^2 flow accumulation threshold, so not all gullies are shown.

an indicator of land degradation (e.g. Wessels et al. 2004; Chen & Rao 2008) and can be used as an indicator of ecosystem recovery following restoration management (Malmstrom et al. 2008). NDVI is a good metric across a wide variety of biomes, although it can saturate due to high near-infrared (NIR) reflectance from soils in some low biomass and high leaf area index (LAI) systems. NDVI was calculated using the red (RED) TM Band 3 (0.63–0.69 μm) and NIR TM Band 4 (0.76–0.90 μm), where:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})}$$

A 3 × 3 low pass filter was applied to smooth the NDVI values in each image to account for inter-annual variability and any remaining pixel offset from the co-registration process. A mask was created to account for areas within the study area that may have unreliable NDVI values. Cover types in the study area were classified with a maximum likelihood supervised classification, using pixels from regions of interest (ROIs) defined by areas of known cover types. Rock outcrops, sparsely vegetated areas (convex shale outcrops with sparse vegetation), roads, shadow, and glint areas (pixels with abnormally high digital number values) were included in the mask. As NDVI values in these areas were considered unreliable or unaffected by watershed management, they were aggregated to create the RockOutcrop mask. Some bare portions of river channels and gullies were misclassified as rock outcrop. Therefore, a terrain analysis was performed, using the DEM as input, and a second layer (WetLayer) was created to capture any areas of the channel bottom that had been misclassified as rock outcrop. The WetLayer was defined as any areas that were both concave and less than 10° hillslope angles, and these pixels were then removed from the RockOutcrop mask. The resulting mask focused the sample area on the channels and adjacent valley bottoms, as well as gently sloping, well-vegetated Puna grassland slopes. Agricultural fields were harvested and bare during the image period, so most terraced fields were masked out. As the images were too cloudy during the rainy season, the effect of terraces on agricultural production could not be measured. Of the total of 262.57 km^2 in the study basins, 96.29 km^2 was masked out, leaving a total of 167.28 km^2 or 63.47% of the study basins for the study analysis.

Points were selected in gullies with check dams in the HighRMI basins and in gullies without check dams in the NonProject basins, to focus the time series analysis on the effect of check dams in gullies and to differentiate between local- and basin-scale effects (Fig. 2). The points were identified based on ground-truthing conducted in 2012 and from Google Earth® imagery taken on 8 August, 2009 and 10 August, 2010. A total of 52 CheckDam points and 65 NoCheckDam points were identified. Note that the five line transects with check dams within the project area were included as CheckDam points. A 3×3 cell grid (nine 30×30 m pixels) was defined around each point to account for the linear nature of the gully feature, as well as a hypothesized 30–50 m effect of check dams on either side of the gully due to increased soil moisture and bank stabilization. Following application of the mask that removed some pixels from the sample, the sample size was 405 pixels (36.45 ha) for the 52 CheckDam points and 501 pixels (45.09 ha) for the 65 NoCheckDam points. NDVI values were extracted for these points for each year to construct a time series. A change detection analysis was also conducted by taking the mean of the four pre-project years (1986–1992) and the four post-project years (2005–2009). The ΔNDVI was then calculated by subtracting the pre-project from the post-project mean NDVI values. The mean difference in ΔNDVI between the CheckDam points and NoCheckDam points was evaluated through a t-test using the Welch–Satterthwaite correction assuming unequal variance and through the independent samples Kolmogorov–Smirnov test.

A change detection analysis was also conducted at the basin level. As deviations from normal trends in NDVI can be used as a proxy for land restoration or continued degradation (Bai et al. 2008), the long-term regional trend in NDVI (1986–2009) was evaluated through a linear regression conducted on NDVI values in the unmasked portions of the study area. The trend in NDVI over time (increasing, decreasing, or the same) was interpreted as the slope of the regression. The ΔNDVI histograms were then evaluated to determine if the between-basin differences were greater at the tails than at the median. The ΔNDVI values were segregated by percentiles to perform a quantile regression (Koenker & Hallock 2001; Cade & Noon 2003) using the median, 12.5 percentile, and 87.5 percentile. Selection of quantile size was based on a sensitivity analysis using increments of 2.5 percentiles to determine the optimal percentile, defined as the largest percentile that captured the greatest difference in ΔNDVI values between basins. The number of pixels in the 12.5 and 87.5 percentiles was then converted into areas and percentage of land surface. This allowed quantification of areas in each basin that were exhibiting a significant increase in greenness, and areas that were the same over time or exhibiting a decrease in greenness. Pearson's correlations ($n = 12$, significance level $= 0.05$) were performed between ΔNDVI in each basin (median, the percentage of land area in the 12.5 percentile, and the percentage of land area in the 87.5 percentile) and the following variables: RMI, total number of check dams, terraces, infiltration ditches, and total ECSs. A step-wise regression was also performed to evaluate if any combination of check dams, terraces, and infiltration ditches best explained variability in ΔNDVI.

Other Data Sources

The project history was documented in CEADB project records that include community sketch maps, erosion control construction records, quarterly and annual progress reports, results of participatory workshops, and working papers and thesis from Núr University and the Universidad de San Simon Agroecology program (AGRUCO) in Bolivia. B.D.H. conducted prior research in the area in 1996, a reconnaissance survey in 2008, and a household survey ($n = 237$) in 2012 which provided demographic and outmigration data.

Results

Line Transects

Bofedal percent cover was significantly higher in gullies with check dams compared to gullies without check dams (Fig. 3). There was no significant difference when comparing the percent cover of grassland. Percent cover of standing water was significantly higher in gullies with check dams; however, standing water was present in some gullies without check dams as well, especially at knick points where gullies had eroded down to the bedrock. The percent cover of bare ground was significantly higher in gullies without check dams (Fig. 3), and the disaggregated data on particle sizes show that there was significantly higher percent cover of exposed bedrock ($p = 0.007$) and cobbles ($p = 0.001$) in gullies without check dams (Table S1, Supporting Information). Channel depth was significantly lower in gullies with check dams compared to gullies without check dams (mean difference $= 1.53$ m, $p = 0.003$), but there was no significant difference when comparing channel width and contributing catchment area (Table S2).

Remote Sensing

The NDVI time series was characterized by high inter-annual variability and a long-term, positive change in greenness

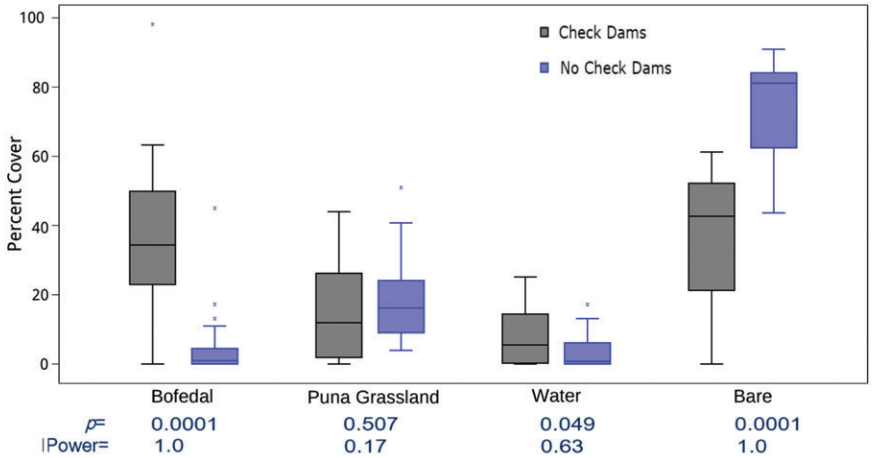

Figure 3. Percent cover of bofedal vegetation, Puna grassland, water, and bare substrate (including bedrock, sand and gravel, and cobbles) in gullies with check dams and gullies without check dams. The box-and-whisker plots show the median, 75th percentile, 25th percentile, and maximum–minimum values, with outliers symbolized with an *x*. Data are from four 25-m line transects established in each gully, and transects were established in five gullies with check dams and five gullies without check dams ($n = 5 \times 4 \times 2$). The *p*-values are from a Brown–Forsythe one-way ANOVA, following a Levene's *F*-test for equality of variances.

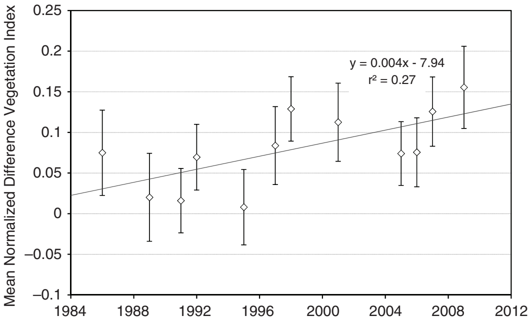

Figure 4. Time series (1986–2009) of normalized difference vegetation index (NDVI) (± SD) for the study area. Data from Landsat TM5 images taken from the same time period (12 May–3 June) in each sample year. The trend line is based on a linear regression ($p < 0.0001$) using the 1986–2009 NDVI values from the unmasked pixels in the study area. The disaggregated time series comparing the HighRMI, LowRMI, and NonProject basins are shown in Figure S1.

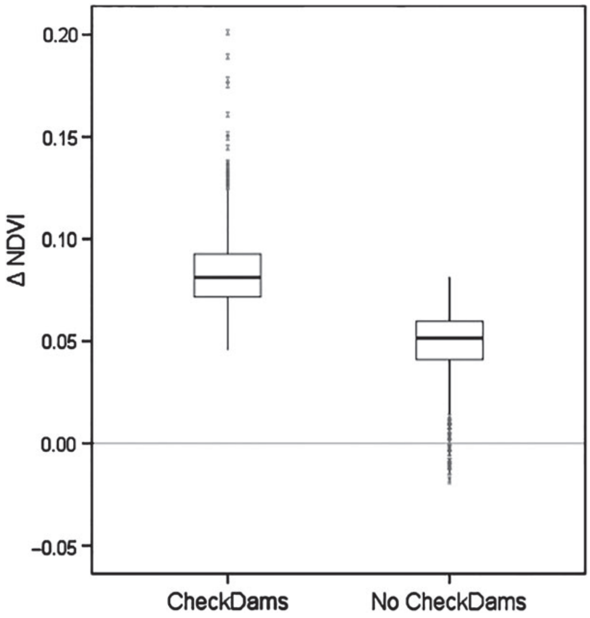

Figure 5. Change in NDVI in points with CheckDams ($n = 405$ pixels) and points with NoCheckDams ($n = 501$ pixels). Data are based on a change detection analysis between the $\bar{x}$ PreProject NDVI (1986–1992) and the $\bar{x}$ PostProject NDVI (2005–2009). Mean difference = 0.036, $t(796.6) = 26.97$ ($p < 0.0001$). The box-and-whisker plots show the median, the 75th percentile, the 25th percentile, and the maximum–minimum values, with outliers symbolized by an *x*.

(Fig. 4), and this trend was similar across the HighRMI, LowRMI, and NonProject basins (Fig. S1). Based on the slope of the linear regression, there was a 4.0% increase in NDVI from 1986 to 2009 ($p < 0.0001$). Moreover, the change detection analysis (ΔNDVI) was positive in 99.7% of the pixels in the study area. Evaluation of the histograms (Fig. S2) shows that although the magnitude of change varies a positive trend in ΔNDVI exists in all basins (median ΔNDVI = 0.0551–0.0720).

The NDVI time series in the CheckDam points ($n = 405$ pixels) and NoCheckDam points ($n = 501$ pixels) showed a similar pattern of general increase in NDVI (Fig. S3). However, the CheckDam points have a significantly higher ΔNDVI (Fig. 5) with the mean difference = 0.036 ($p < 0.0001$). Moreover, based on the Kolmogorov–Smirnov test of normality there is a skew in the distributions, insofar as the CheckDam points had a higher proportion of extremely high ΔNDVI values ($p < 0.0001$) and the NoCheckDam points had a higher proportion of extremely low ΔNDVI values ($p < 0.0001$). Therefore, a statistically significant mean difference was confirmed through the nonparametric Kolmogorov–Smirnov test ($p < 0.0001$).

A basin scale comparison of the ΔNDVI values segregated by percentiles (Table S3; Figs. 6 & S3) revealed an association between ECSs and the median, 12.5 percentile, and

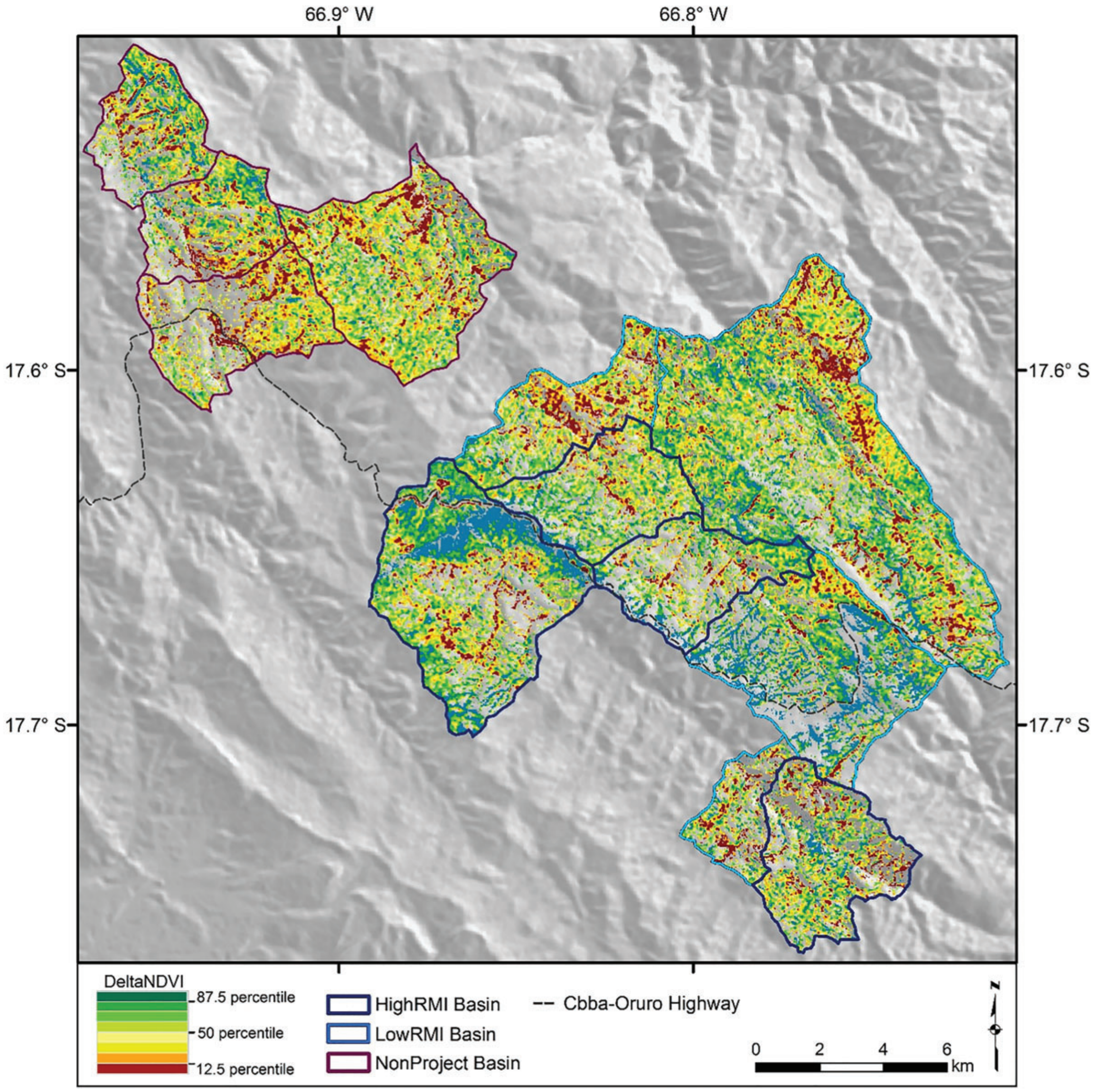

Figure 6. Change in greenness in the study area. ΔNDVI based on a change detection analysis between the $\bar{x}$ PreProject NDVI (1986–1992) and the $\bar{x}$ PostProject NDVI (2005–2009). Data are segregated by 12.5 percentiles. The spatial distribution of the 12.5 percentile and the 87.5 percentile of ΔNDVI in the HighRMI, LowRMI, and NonProject basins is shown in Figure S4.

87.5 percentile values across all basins, but the variability is high. Based on Pearson's correlations, the number of check dams is the strongest predictor of ΔNDVI (Table 3). Higher numbers of check dams were correlated with higher median ΔNDVI values, higher percentage of land area in the 87.5 percentile, and lower percentage of land area in the 12.5 percentile. Higher RMI values were correlated with lower percentage of land area in the 12.5 percentile, and total ECSs were correlated with lower median ΔNDVI and lower percentage of land area in the 12.5 percentile. There was no statistically significant association between terraces and infiltration ditches and ΔNDVI values, nor did any combination of check dams, terraces, and infiltration ditches in a step-wise regression improve the prediction of ΔNDVI values.

Discussion

The ground measurement through line transects indicates that building check dams increases bofedal vegetation in gullies. There is also a shift from bedrock and cobbles to finer particle size distribution, a decrease in gully depth, and an increase in standing water in gullies with check dams. This is consistent with findings of other field studies that check dams reduce flow velocities, trap fine sediments, change longitudinal gradients, and increase moisture retention (Castillo et al. 2007; Boix-Fayos et al. 2008; Hassanli et al. 2009), leading to greater wetland ephemeral and riparian vegetation cover (Bombino et al. 2008, 2010). Check dams do not influence Puna grassland cover on the immediate banks of the central thalweg; however, the effect of increased soil moisture on grassland productivity

Table 3. Correlation of RMI, total number of erosion control structures (ECSs), and total ECSs with the 12.5 percentile, median, and 87.5 percentile of ΔNDVI. The 12.5 and 87.5 percentiles were converted to percent land surface for each basin. $N = 12$, significance level = 0.05, and statistically significant percentiles are shown in bold.

	Lower 12.5%		*Median ΔNDVI*		*Upper 87.5 %*	
	Person Correlation	*Sig (1-Tailed)*	*Person Correlation*	*Sig (1-Tailed)*	*Person Correlation*	*Sig (1-Tailed)*
RMI	**−0.518**	**0.042**	0.422	0.086	0.311	0.163
Check dams	**−0.628**	**0.014**	**0.640**	**0.013**	**0.594**	**0.021**
Terraces	−0.474	0.060	0.463	0.065	0.439	0.077
Infiltration ditches	−0.214	0.252	0.179	0.289	0.182	0.286
Total ECSs	**−0.521**	**0.041**	**0.511**	**0.045**	0.483	0.056

was not measured. In addition, Puna grassland cover may increase at the top of the channel banks provided check dams contribute to gully stabilization and decreased slumping (Lal 1992; Boix-Fayos et al. 2008).

To relate ground measurements to remote sensing data, we first discuss the long-term trends in NDVI, and account for other variables in addition to restoration management that may explain changes in greenness (ΔNDVI). The time series of NDVI reveals a 4.0% increase across the study area. This is consistent with Bai et al. (2008), who found that although land degradation was occurring in 24.3% of the Earth's land surface, there were regenerating areas as well. This resulted in a net 3.8% global increase in NDVI and a 4.4% increase in Latin America. Reasons for the increase in greenness observed in the study area include climate change and reduced land use pressure (Olsson et al. 2005; Bai et al. 2008). Although the frequency of extreme precipitation events is increasing, there has been no significant increase or seasonal shift in precipitation that would account for the increase in greenness in the eastern cordillera of the Andes (Thibeault et al. 2010; Seiler et al. 2013; Boers et al. 2014). There is, however, a trend toward slightly drier conditions on the Western cordillera of the Andes in southern Peru and western Bolivia (Vuille et al. 2003). Increased NDVI across the study area is more likely due to a temperature increase of 0.9–0.15°C per decade since 1939 (Vuille & Bradley 2000; Vuille et al. 2003, 2015; Bradley et al. 2006; Thibeault et al. 2010; Seiler et al. 2013). High-elevation biomes are particularly sensitive to increased temperature, with species or whole vegetation zones expected to migrate to higher elevations (Benniston 2003) provided suitable soils are available (Lee et al. 2005). Local people report that t'ola (*Baccharis* spp.), a common shrub in the region, has colonized high-elevation Puna grasslands in recent years, and this could lead to higher NDVI values.

The second reason for the increase in greenness in the study area is reduced land use pressure due to outmigration. People have been moving to the cities and the lowland tropics at high rates throughout the Andes (Suarez & Torrealba 1982; Zimmerer 1993; Gray 2009), and approximately 45.4% of families have moved out of the study area since the 1990s (Hartman 2014). Previous studies have found that outmigration and increased reliance on off-farm labor can lead to regeneration in grassland and forest biomes due to land abandonment, consolidation of agricultural activities on the most productive lands, and reduced pressure from grazing and wood harvest (Grau et al. 2003; Olsson et al. 2005; Baptista & Rudel 2006; Kull et al. 2007; Izquierdo et al. 2008).

Given the long-term increase in NDVI in the study area, evaluation of land degradation and restoration must be done in the context of deviations from the normal trend. At the local scale the change detection analysis indicated greater ΔNDVI in CheckDam points compared to NoCheckDam points, consistent with the increased bofedal cover observed in the line transects. There was also a correlation between check dams and ΔNDVI at the landscape scale. We take the 87.5 percentile to represent recovering areas indicative of land restoration, and the 12.5 percentile to represent the areas where continued land degradation has occurred. Although there is high spatial variability, and land restoration and continued land degradation areas exist in all basins, greater restoration management leads to an increase in land restoration areas and a decrease in land degradation areas.

Spatially, there is a strong association between the Cochabamba-Oruro Highway and ΔNDVI, with a corridor of high ΔNDVI values that extends up to 1.2 km from the central road where the density of ECSs is the highest. The land restoration areas are very large (46.9–610.6 ha per project participant communities), and are greater than the surface area covered by check dams. There are over 30 communities in the entire project area, with an estimated 49.3 km^2 of total land area affected by restoration activities after accounting for regeneration rates in NonProject communities. Other wet meadow restoration studies found that grade control structures that accumulate sediment in incised gullies raised water tables and contributed to vegetation recovery in a buffer zone up to 100-m on either side of the channel (Shields et al. 1995; Schilling et al. 2003; Loheide & Gorelick 2007; Loheide & Booth 2011). We speculate that check dams affect bofedal and grassland vegetation in a broader area by raising water tables relative to surface vegetation, a conclusion that deserves further research.

Land restoration yields important ecosystem services for local communities. Bofedales provide vital dry season grazing, and increased bofedal vegetation due to check dams can contribute to grazing stability (Preston et al. 2002; Washington-Allen et al. 2008). The increased standing water associated with check dams also has implications for water security in arid and semiarid lands (Scott et al. 2013), contributing to groundwater recharge and stabilization of downstream water flows (Bouwer 2002). It is often assumed that farmers will not sustain watershed management over long time periods and large spatial scales (Valentin et al. 2005). However, this study suggests that when land restoration is aligned with the provision of ecosystem services for local communities, extensive land restoration can be achieved even under continued agriculture and grazing management.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Percent cover of particle size classes in the bare ground portion of gullies with check dams compared to gullies without check dams.

Table S2. Channel geometries and upstream basin areas in gullies with check dams compared to gullies without check dams.

Table S3. Estimation of areas of land restoration/regeneration and continued degradation/arrested succession at the study communities.

Figure S1. Disaggregated time series (1986–2009) of NDVI ($\bar{x} \pm$ SD) for the study area, comparing the HighRMI, LowRMI, and NonProject basins.

Figure S2. Histograms of the change detection analysis (ΔNDVI) conducted by subtracting the mean NDVI values of the four pre-project years (1986–1992) from the four post-project years (2005–2009).

Figure S3. Time series (1986–2009) of NDVI for the 52 CheckDam points ($n = 405$ pixels) in gray and the 65 NoCheckDams ($n = 501$ pixels) in blue.

Figure S4. Spatial distribution of the 12.5 percentile and the 87.5 percentile of ΔNDVI in the study area basins.

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