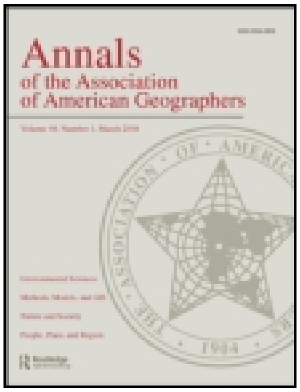

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Mountain environments, including the Andean *páramo* grasslands of Ecuador, are important water source areas. They are often sites of programs and policies intended to achieve multiple management objectives, such as carbon sequestration, biological conservation, and water resource protection; yet such environments are often data poor. This creates challenges for programs that compensate landowners for protecting ecosystem services and uncertainty regarding which land uses are compatible. For example, does afforestation for carbon sequestration complement or hinder efforts to protect water resources in Andean páramos? We compared characteristics of high-elevation soil profiles at sites in two Ecuadorian páramo study areas and measured soil–water properties to assess whether changes in land use affected the soil hydrology. Using a space-for-time substitution, we compared soils in plantations of pines and *Polylepis racemosa* in grasslands with different grazing and burning regimes. Methods included soil description in soil pits; soil moisture measurement in soil pits and across surface transects; tracer studies of soil–water movement; and laboratory determination of bulk density, particle size, and humic acid composition. Of the land uses examined, only afforestation significantly affected soil moisture, whereas soil properties did not differ among grassland burning and grazing regimes. The results suggest that afforestation of páramos hinders the production of water and they underscore the need for further investigation to inform the trade-offs needed in managing páramo landscapes to support multiple ecosystem services. *Key Words: afforestation, ecosystem services, páramo grassland, soil moisture, water resources.*

高山环境, 包含厄瓜多安地斯山的稀疏高原草原, 是相当重要的水资源地区。它们经常是各项计画与政策预期达成多重管理目标的场域, 例如碳截存、生物保育, 以及水资源保护; 但此一环境却经常缺乏研究资料, 因而造成为了保护生态系统服务对地主进行补偿计画的困难, 以及有关何为相容土地使用的不确定性。举例而言, 为了碳截存进行造林, 到底有助于还是会阻碍安地斯山稀疏高原的水资源保护呢? 我们比较两个厄瓜多稀疏高原研究区中高度演化的土壤剖面, 并测量土壤的水份特性, 评估土地使用的改变是否会影响土壤水文。我们运用空间替代时间研究法, 比较在有着不同放牧与火势的草原中种植松树与*Polylepis racemosa*之林场的土壤。研究方法包含在土坑中的土壤性质描述、土坑以及横跨表层横切的土壤水分测量、土壤水运动的示踪研究, 以及土体密度、粒径与腐殖酸组成的实验室确认。在检视的土地使用中, 只有造林显着地影响土壤水分, 而草原火烧与放牧地带的土壤性质并没有差别。研究结果显示, 稀疏高原的造林阻碍了水的生产, 并强调需要进一步的调查以知晓管理稀疏高原地景时所需权衡的代价, 并进而支持多重生态系统服务。 *关键词: 造林, 生态系统服务, 丛生草甸草原, 土壤水分, 水资源。*

Los entornos de montaña, incluyendo los pastizales de páramo andino del Ecuador, son importantes áreas generadoras de agua. A menudo estos sitios son objeto de programas y políticas diseñados para buscar múltiples objetivos de administración, tales como secuestro de carbono, conservación biológica y protección del recurso hídrico; pero con frecuencia tales espacios ambientales son pobres en datos. Esto genera retos para los programas que compensan a los propietarios por servicios de protección del ecosistema, e incertidumbre en lo que concierne a los usos del suelo que puedan ser compatibles. Por ejemplo, ¿la reforestación para efectos de secuestro de carbono, complementa o estorba los esfuerzos para proteger los recursos hídricos de los páramos andinos? Nosotros comparamos las características de perfiles del suelo de alta montaña obtenidos en dos áreas de estudio del páramo ecuatoriano y medimos las propiedades suelo–agua para establecer si los cambios en el uso del suelo afectaban la hidrología edáfica. Utilizando una sustitución de espacio por tiempo, comparamos los suelos en las plantaciones de pinos y de *Polylepis racemosa* en pastizales sometidos a diferentes regímenes de pastoreo y quema. Los métodos empleados incluyeron la descripción del suelo en barrancas o descapotes de la superficie; medición de la humedad edáfica en excavaciones y a través de transectos de la superficie; estudios de rastreo del movimiento suelo–agua; y

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determinación en laboratorio de densidad, tamaño de las partículas y composición de ácido húmico de los suelos, en general. De los usos del suelo examinados, solo la reforestación afecta significativamente la humedad del suelo, en tanto que las propiedades del suelo no mostraron diferencias entre los regímenes de quema y pastoreo de los pastizales. Los resultados sugieren que la reforestación de los páramos entorpece la producción de agua, y también subrayan la necesidad de formentar la investigación para informar de las compensaciones que se requieren para el manejo de los paisajes de páramo que sean asiento de múltiples servicios de ecosistema. *Palabras clave: reforestación, servicios ecosistémicos, pastizal de páramo, humedad del suelo, recursos hídricos.*

Like other high mountain regions of the world, the Andes serve as water towers (Messerli, Viviroli, and Weingartner 2004). Human populations in and around the Andes depend on fresh water from rivers that originate in the highlands. In the northern Andes, high-altitude *páramo* grasslands are the dominant ecosystem, estimated to cover 77,000 km^2 (Dinerstein et al. 1995) between elevations of approximately 3,200 m and 4,700 m above sea level (Luteyn 1992). Páramo soils play an important role in regulating water (Buytaert et al. 2006), and more than 10 million people rely on the páramos of the northern Andes for their fresh water (Buytaert, Deckers, and Wyseure 2006). High peaks with glaciers are spatially infrequent, but glacial meltwater is an important water source at some locations (Vergara et al. 2007). In recent decades, individual, local, national, and international drivers have accelerated land-use change in the Andes. Today, changing land uses in the páramo grasslands, the disappearance of glaciers, and increases in population and per capita water demand combine to create concern for the adequacy of future water supply in the region (Bradley et al. 2006; Rhoades 2006).

Recognition of the need to take the full value of ecosystem services, including the provision of freshwater, into account when making decisions about land management (Millennium Assessment Board 2005) has led to increasing numbers of programs that provide compensation for ecosystem services (CES). Some CES programs implemented in developing regions, including Andean Ecuador, also have the intention of alleviating rural poverty (e.g., Tallis et al. 2008; Swallow et al. 2009; Farley et al. 2011). CES programs often have multiple environmental management objectives, such as carbon sequestration, biological conservation, and water resource protection. For developing regions with scarce data resources, decisions about the practices to be supported are often based on limited knowledge and assumptions rather than on tested knowledge of local conditions (Muradian et al. 2010). This has been the case in highland Ecuador.

This study is part of a larger investigation of tradeoffs among ecosystem services in páramo ecosystems of highland Ecuador. In this article, we ask this question: What is the effect of land-use change in páramos on ecosystem services related to water? Specifically, we want to know whether (1) soil properties, (2) soil moisture, and (3) soil–water movement remain the same following land-use change.

Land Use and Land-Use Change in Páramos

Soils in Ecuadorian páramos are primarily Andisols formed from volcanic ash. The grasses of páramo grasslands are bunch grasses with fine, deep root systems, including *Calamagrostis* spp., *Festuca* spp., and *Cortaderia* spp. (Sarmiento and Frolich 2002). Cool, humid conditions promote slow decomposition rates of páramo vegetation (Luteyn 1992), and organometallic complexes formed in volcanic ash resist microbial breakdown (Farley, Kelly, and Hofstede 2004). As a result, páramo soils retain organic matter and their A horizons can be more than 1 m thick. Values of organic carbon as high as 212 g kg^{-1} have been reported for páramo soil (Poulenard et al. 2001). Mean annual temperatures range from 2°C to 10°C (Hofstede et al. 2002), temperatures can reach 0°C at night and 20°C during the day (Buytaert, Iñiguez, and de Bièvre 2007), and precipitation ranges from 700 mm to 3,000 mm during the year, depending on location (Luteyn 1992).

Historically, páramos have been used as grazing lands for cattle, sheep, and horses, and they have been burned every two to three years to remove old grass and allow succulent, nutritious new shoots to emerge. One land-use change promoted by Socio-Páramo, a CES program of the Ecuadorian government, is to reduce grazing and burning (Farley et al. 2011), but the hydrological effects of this policy have not been previously studied. In fact, the water-regulating capacity of the páramo and the effects of land use on its soil–water relationships have been studied by only a handful of researchers (e.g., Podwojewski 1999; Podwojewski et al. 2002; Farley, Kelly, and Hofstede 2004; Buytaert et al. 2005; Buytaert et al. 2006; Harden 2006; Buytaert, Iñiguez, and de Bièvre 2007).

The open spaces of páramo grassland landscapes, seemingly underexploited, have attracted investment from governmental, nongovernmental, and foreign agencies interested in afforestation. Afforestation projects have had goals of timber production, soil and water conservation, and, more recently, carbon sequestration (Farley 2007). Trees are valued for their wood and above-ground carbon sequestration, and forests are valued for their contributions to biodiversity and soil and water conservation (e.g., Klooster 2003). Tree plantations have been successfully established in páramos, but the hydrological consequences of tree planting in páramo landscapes have been studied in only a few locations. Since Pliny the Elder wrote about the association between forest clearance and the appearance of springs (circa 77–79 AD; Plinius 1856), observers have recognized that human-initiated changes to surface vegetation can change local hydrological regimes. Results from studies of the hydrological effects of forest clearance in more than 100 paired watersheds around the world show considerable variability but indicate that forest removal tends to increase water yield (Bosch and Hewlett 1982; Stednick 1996). At the same time, afforestation of grasslands and shrublands has been found to reduce water yield across a range of locations and conditions (Farley, Jobbagy, and Jackson 2005). Trees affect soil characteristics, remove water from the soil, capture atmospheric water that might otherwise pass over, and affect rates of evaporation by providing shade and reducing air flow.

Research on afforestation of pines in páramos includes that of Farley, Kelly, and Hofstede (2004), who found little difference in water retention capacity at saturation between sites in grassland or under pines of increasing age (to twenty-five years) but greater difference among sites at greater degrees of drying. The grassland soils they studied maintained higher water retention capacities, even at the wilting point. In a study of water yields of paired catchments (0.6 to 2.6 km^2), Buytaert, Iñiguez, and de Bièvre (2007) found the grassland catchment in each pair to consistently yield more water than the catchment planted in pine (*P. patula*) or under cultivation. They calculated that pines reduced water yield by approximately 50 percent and provided flow-duration curves to show the ability of grassland catchments to regulate flow.

Although site-specific studies have found significant differences in water retention (Farley, Kelly, and Hofstede 2004) or water yield (Buytaert, Iñiguez, and de Bièvre 2007) between grass páramo and pine plantations, no previous studies have investigated the hydrologic effects of *Polylepis racemosa*, a fast-growing Peruvian species increasingly used in highland afforestation projects. The only previous regional-scale study (Hofstede et al. 2002) was unable to clearly separate the effect of pine plantations from regional differences. They found drier soil under pines than under grassland, but they concluded that the effects of the pines could not easily be generalized.

Our study took a regional approach and used a space-for-time substitution, comparing soil characteristics of páramo sites under different land uses to determine whether changes in land use affect the storage and transmission of water in páramo soils. Our objective was to determine whether differences in soil properties, soil moisture, and water movement in the soil differed among plots representing different land uses at different locations in the Ecuadorian Andes. The land uses studied—afforestation with pine (*Pinus radiata*, *Pinus patula*) or *Polylepis racemosa* and grasslands with different frequencies of burning, exclusion of burning, and exclusion of grazing—represent those being promoted to allow these landscapes to support the ecosystem services of water provision, carbon capture and storage, and biodiversity.

Study Areas

We selected two study areas, one in northern Ecuador and one in the southern part of the country (Figure 1). The northern study area is in the community of Zuleta (0.20°N, 78.00°W), in the province of Imbabura. The highland grassland was used for cattle grazing in recent centuries but now is managed to provide water for seventeen communities and part of the city of Ibarra. *Pinus radiata* were planted about forty years ago on a one-hectare plot, and in 2001 the community began planting *Polylepis racemosa*. An additional 20,000 ha of *Polylepis* were added in 2007. One stand of *Polylepis*, planted in 2001 in a field where potatoes had been cultivated previously, contains trees 3 m tall. Some portions of the property are grazed by alpacas.

The southern study area is in the Mazar Wildlife Reserve (2.50°S, 78.70°W), in the province of Cañar. Much of the Reserve is in páramo grassland, but middle and lower elevations contain montane forest, areas planted with *Pinus patula*, and areas dominated by shrubs and small trees. Stands of pines had been planted approximately twenty years earlier under a government program that provided incentives for plantation forestry. The Reserve is managed by the Fundación

Figure 1. Locations of the Zuleta and Mazar Wildlife Reserve study areas.

Cordillera Tropical as a wildlife reserve and used for alpaca husbandry.

Sites within each study area were similar in climate, soil, elevation, and slope angle, so that they differed only by land use (Table 1). Soils at both study areas are histic Andisols. All sites were known to have been grass páramo in the past, either from conversations with land managers or from Landsat images (Mazar Reserve). Of seven sites at the Zuleta study area, one was in the forty-year-old stand of *Pinus radiata*; one was in a stand of 3-m tall, eight-year-old *Polylepis racemosa* trees; and the others were in páramo grassland, with differences among them based on the time since most recent burning, presence or absence of *Polylepis* trees, or presence or exclusion of grazing. All sites had a long history of grazing and burning; the Zuleta ZAg-P site had the additional, unique history of having been previously used for potato cultivation. Of seven sites at the Mazar Reserve, two were in stands of approximately twenty-five-year-old *Pinus patula* and one was at a formerly grassland site that had not burned in approximately forty to fifty years and supported a mixture of shrubs, small trees, and grasses. Two of the four sites in grass páramo had been recently burned; one had not burned for six years; and one, containing a mixture of grass and shrubs, had not burned for about twenty-five years.

Research Methods

In this substitution of space for time, we investigated the effects of land-use change on soils and soil hydrologic characteristics at seven sites in each of the two study areas. Fieldwork was completed in June and July of 2009 and 2010. To compare sites and study areas, and to better understand these unusual soils, we first described them. At each site (except ZUB-3 and MG),

Table 1. Characteristics of the study sites at Zuleta (Z) and the Mazar Wildlife Reserve (M)

Site	Elevation (m)	Slope (degrees)	Land use
ZB	3,625	20	Bunch grass; burned nine months earlier; small *Polylepis*; no grazing
ZUB-P-1	3,608	12	Bunch grass; burned twelve years earlier; *Polylepis*; alpaca grazing
ZUB-P-2	3,648	11.5	Bunch grass; burned and grazed until fifteen years earlier; some small *Polylepis*
ZUB-P-3	3,635	12	Bunch grass; burned fifteen years earlier; *Polylepis*; no grazing
ZUB-1	3,656	13	Bunch grass; burned nine years earlier; grazing, no trees
ZUB-2	3,643	12.5	Bunch grass; burned fifteen years earlier; no trees
ZPine	3,598	16	Pines (forty years old), previously grazed and burned
ZAg-P	3,518	12	*Polylepis*; field was in potatoes until ten years earlier, with fertilizer added; *Polylepis* for eight years; alpaca grazing
M1Y	3,449	21	Bunch grass; burned seven months earlier; alpaca grazing
M6Y	3,428	20	Bunch grass; burned six years earlier; occasional woody shrubs; alpaca grazing
M25Y	3,453	13.5	Burned twenty-five years earlier; woody shrubs with some bunch grass
M45Y	3,351	22	Has not been burned in at least forty-five years; shrubs, young trees
MP-1	3,402	17.5	Pine plantation (approximately twenty years old)
MP-2	3,249	20	Pine plantation (approximately twenty years old)
MG	3,299	~17	Bunch grass; frequently burned, approximately every two to three years; seasonally grazed by cattle; adjacent to and outside of the Reserve

Note: For the Zuleta (Z) sites: B = burned within one to three years; UB = not burned for nine to fifteen years; P = planted with *Polylepis racemosa*. For Mazar (M): grass sites are MxY, where x is years since last burn; P = pine, MG = a grass site outside of the Reserve.

we dug a 1-m-deep soil pit, described and classified the soil, and extracted samples horizontally from each A horizon for later determination of bulk density and particle size. We obtained in situ, instantaneous measurements of volumetric soil moisture content (VMC) using a Campbell Hydrosense water content sensor (CS620) with 12-cm time-domain reflectometer probes. VMC was measured in each A horizon in the soil pits and at multiple points across surface transects. We obtained a total of 650 VMC measurements on transects at Zuleta and 555 VMC measurements at the Mazar Reserve. At Zuleta, we completed an additional, smaller set of measurements ($n = 50$) within a two-hour period for comparison with results that had been obtained on different days. Wet weather prevented us from completing a two-hour comparison at the Mazar Reserve. We used analysis of variance and Tukey's all-pairs comparison to assess the significance of differences in VMC among sites.

Two field methods were used to trace soil–water movement. First, we applied a KBr tracer dissolved in water to a small plot and extracted soil samples over a two-hour period. In this procedure, we used one liter of 500-ppm KBr solution over a 0.38 m^2 plot on bare soil. The liquid tracer test was done at three Zuleta sites: one in pine, one in grass, and one at a recently burned grassland site. The test was also done at two Mazar Reserve sites: one in pine and one at a recently burned grassland site (Hartsig 2011). In a second, longer term test, we sprinkled 500 g of dry KBr crystals over a plot measuring 2 m^2 and returned one year later to recover samples. This was done at two sites in each study area: a recently burned grass site and a pine site. Soil samples were taken in and downslope of the plot at specified depths and distances (Hartsig 2011).

Bulk density, particle size (laser diffraction), bromide concentrations, and the melanic index of the soil were determined at the University of Tennessee. Melanic index values were determined using a spectrophotometer (Hartsig 2011).

Results

Soil Properties

Soil descriptions from fourteen soil pits, seven at each study area, showed much similarity in páramo soils between study areas and among sites (Table 2). Most striking were the A-horizon depths and deeply black soil colors. Zuleta sites had three A horizons, with combined depths of over 100 cm. Soils in the Mazar Reserve were not as deep, with two A horizons 61 to 91 cm deep overlying a 2Bw and 2Cr horizon. The most notable differences in the physical properties of the soil were in soil structure and moisture consistency between grassland and pine sites. Surface horizons at two pine sites (ZPine and MP1) had granular structures, whereas grass sites, pine site MP2, and subsurface horizons at all sites had moderately to strongly subangular structures. At Zuleta, all A1 horizons had the same pattern of moisture consistence: very friable in A1 horizons and friable in other A horizons. At the Mazar Reserve, moisture consistence of the A1 horizon was more friable in A1 horizons of the two pine sites than at all other sites.

Soil bulk densities were low across all sites, ranging from 0.27 g cm^{-3} to 0.86 g cm^{-3}. Zuleta soils had higher bulk densities (median 0.71 g cm^{-3}) than those at the Mazar Reserve (median 0.45 g cm^{-3}). At Zuleta, the A1 horizons with highest bulk densities were at sites with trees (pine, 0.71 g cm^{-3}; *Polylepis*, 0.79 g cm^{-3}). At the Mazar Reserve, the relationship between soil bulk density and afforestation was not evident: The A1-horizon bulk density of one pine site (MP2, 0.42 g cm^{-3}) exceeded the average for the reserve (0.36 g cm^{-3}), whereas the lowest bulk density value was from the other pine site (0.27 g cm^{-3} at MP1).

Soil Moisture

Instantaneous measurements of soil moisture in each horizon of the soil pits documented high VMC and a small decrease with depth. At Zuleta, soil was significantly drier under pines, having VMC of 13 percent to 22 percent compared to 50 percent to 74 percent at grassland sites. VMC of 45 percent to 53 percent at site ZAg-P (*Polylepis* in a former potato field) was significantly different from and intermediate between that of grassland and pine sites. VMC readings in soil pits at the Mazar Reserve were higher than those at Zuleta. Whereas soil-pit VMC at Zuleta ranged from 13 percent to 22 percent in pine and 45 percent to 74 percent at other sites, soil-pit VMC at the Mazar Reserve was 63 percent to 86 percent under pine, 73 percent to 86 percent under grass, and 81 percent to 89 percent under a transitional site. This small set of soil-pit VMC measurements, with one point per horizon, provided a three-dimensional context for the hundreds of measurements of VMC at 0 cm to 12 cm depth obtained across surface transects.

Table 2. Soil properties of the study sites at Zuleta (Z) and the Mazar Wildlife Reserve (M)

Site	Horizon	Depth (cm)	Color	Texture	Structure	Moisture consis-tence	VMC%	Bulk density g cm^{-3}	Land use
ZB	A1	23	10 YR N/0	SiL	ST SBK	Very friable	71	0.55	Bunch grass burned nine months earlier; *Polylepis racemosa* planted but small and dispersed; no grazing
	A2	50	10 YR 2/1	SiL	ST SBK	Friable	60	0.59	
	A3	>86	10 YR 2/2	SiL	ST SBK	Friable	53	0.54	
ZUB-1	A1	25	7.5 YR 2.5/1	SiL	ST SBK	Very friable	71	0.60	Bunch grass; burned nine years ago; grazing, no trees
	A2	43	10 YR 2/1	SiL	ST SBK	Friable	66	0.67	
	A3	65	10 YR 2/1	SiL	ST SBK	Friable	58	0.81	
	AC	>105	7.5 YR 2.5/2	L	MA	No data	50	No data	
ZUB-2	A1	24	10 YR N/0	SiL	ST SBK	Very friable	68	0.59	Bunch grass; burned fifteen years ago; no trees
	A2	49	10 YR 2/1	SiL	ST SBK	Friable	62	0.67	
	A3	>72	7.5 YR 2.5/1	SiL	ST SBK	Friable	56	0.83	
ZUB-P-1	A1	26	7.5 YR 2.5/1	SiL	ST SBK	Very friable	70	0.56	Bunch grass burned twelve years ago; *Polylepis racemosa*; alpaca grazing
	A1	58	7.5 YR 3/1	SiL	ST SBK	Friable	59	0.78	
	AC	>115	7.5 YR 2.5/2	L	MA	No data	56	0.85	
ZUB-P-2	A1	21	10 YR N/0	SiL	ST SBK	Very friable	74	0.51	Bunch grass; burned and grazed until fifteen years ago; some small *Polylepis racemosa*
	A2	43	10 YR 2/1	SiL	ST SBK	Friable	68	0.59	
	A3	≥76	7.5 YR 2.5/1	SiL	ST SBK	Friable	62	0.73	
ZPine	A1	24	10 YR 2/1	SL	MO Gr	Very friable	22	0.71	Pines (forty years old), previously grazed and burned
	A2	42	10 YR 2/1	L	MO SBK	Friable	20	0.82	
	A3	65	10 YR 2/1	L	MO SBK	Friable	13	0.86	
	AC	>96	10 YR 2/2	L	MO SBK	Friable	No data	No data	
ZAg-P	Ap	19	10 YR 2/1	SiL	ST SBK	Very friable	52	0.79	Field previously in potato cultivation; *Polylepis* for past eight years; alpaca grazing
	A1	56	7.5 YR 2.5/1	SiL	ST SBK	Friable	53	0.79	
	AC	>94	7.5 YR 2./5/1	L	MA	No data	45	0.84	
M1Y	A1	18	10 YR 2/1	SiL	MO SBK	Friable	79	0.46	Bunch grass burned seven months earlier; bare areas
	A2	45	10 YR 2/1	SiL	MO SBK	Friable	73	0.54	
	2Bw	79	7.5 YR 2.5/2	SiL	MO SBK	Friable	66	0.8	
	2C	>120	7.5 YR 5/6	L	MA	No data	49	No data	
M6Y	A1	24	10 YR 2/1	SiL	MO SBK	Friable	86	0.31	Bunch grass burned six years earlier; occasional woody shrubs
	A2	45	10 YR 2/1	SiL	MO SBK	Friable	84	0.79	
	2Bw	75	7.5 YR 2.5/2	SiL	MO SBK	Friable	79	0.51	
	2C	>110	5 YR 4/6	L	MA	No data	66	No data	
M25Y	A1	22	10 YR 2/1	SiL	MO SBK	Friable	89	0.34	Burned twenty-five years ago; woody shrubs with some bunch grass
	A2	53	10 YR 2/1	SiL	MO SBK	Friable	81	0.48	
	2Bw	76	7.5 YR 2.5/2	SiL	MO SBK	Friable	73	0.52	
	2C	>98	7.5 YR 4/6	L	MA	No data	60	No data	
M45Y	A1	22	10 YR 2/1	SiL	MO SBK	Friable	No data	0.37	Burned forty to fifty years ago; shrubs, young trees
	A2	43	10 YR 2/1	SiL	MO SBK	Friable	No data	0.50	
	2Bw	61	7.5 YR 2.5/2	L	MO SBK	Friable	No data	0.65	
	2C	>77	No data	No data	No data	No data	No data	No data	
MP1	A1	26	10 YR 2/1	SiL	MO Gr	Very friable	63	0.27	Pines (approximately twenty years old)
	A2	57	10 YR 2/1	SiL	MO SBK	Friable	86	0.32	
	2Bw	83	7.5 YR 2.5/1	SiL	MO SBK	Very friable	82	0.39	
	2C	>124	5 YR 5/6	L	MA	No data	72	No data	
MP2	A1	25	10 YR 2/1	SiL	MO SBK	Very friable	76	0.42	Pines (approximately twenty years old)
	A2	52	10 YR 2/1	SiL	MO SBK	Friable	75	0.44	
	2Bw	91	7.5 YR 2.5/1	SiL	MO SBK	Very friable	76	0.48	
	2C	>100	7.5 YR 4/4	L	MA	No data	65	No data	

Note: No soil pit data were available for ZUB-P-3 or MG. For the Zuleta (Z) sites: B = burned within one to three years; UB = not burned for nine to fifteen years; P = planted with *Polylepis racemosa*. For Mazar (M): grass sites are MxY, where x is years since last burn; P = pine. For soil structure: ST = strongly; MO = moderately; SBK = subangular blocky; Gr = granular; MA = massive.

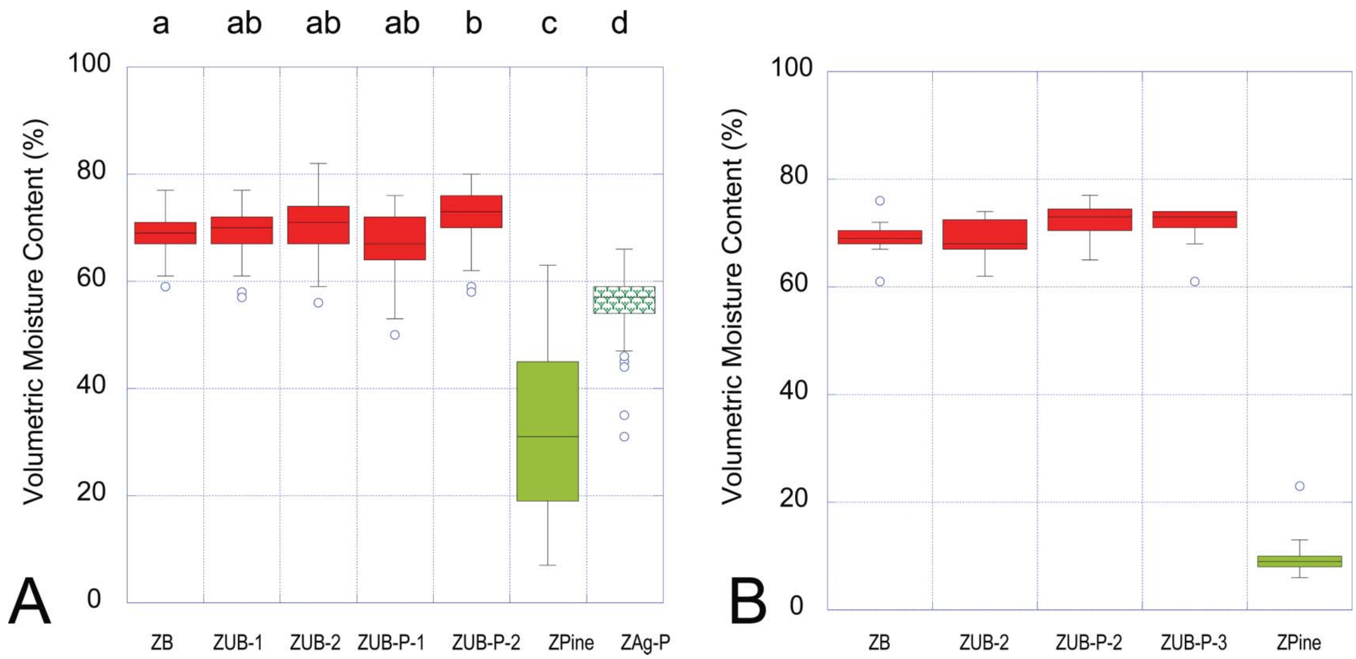

Figure 2. Soil moisture in the upper 12 cm of soil across the sites at Zuleta. (A) $n = 650$, taken over the course of a week; (B) $n = 50$, taken at five sites over a two-hour period. The horizontal bar in each box is the median value; the upper and lower bounds of the box are the first quartile above and below the median. Red shading indicates grassland; letters a–d indicate significantly different volumetric moisture content values. (Color figure available online.)

Spatial variability of surface-soil moisture was significantly greater at tree plantation than grassland sites (Figure 2A). At Zuleta, surface soil was driest at the pine site (ZPine) and significantly drier at the *Polylepis* (ZAg-P) site than at grassland sites. A second set of comparative measurements at Zuleta (with fewer points but completed within two hours) confirmed those soil moisture patterns, including the absence of a soil moisture signal from young *Polylepis racemosa* planted among grasses (Figure 2B). Surface soils at both Mazar Reserve pine sites were significantly drier than those at other sites and differed from each other (Figure 3). Site M45Y (approximately forty-five years unburned) had intermediate VMC values. As at Zuleta, VMC varied more under pine plantations than under grassland. In both study areas, surface soils at recently burned grassland sites had high moisture contents with little spatial variability, and the moisture content of recently burned sites did not differ significantly from that of other grassland sites.

Water Movement in Soil

The two-hour tracer test demonstrated instances of rapid movement of the KBr solution through the soil profile and more uniform penetration of water under grass than pine. Bromide concentrations were low under pines compared to grassland. At the Mazar Reserve, the solution did not penetrate below 20 cm in the grassland plot and was detected in only six (of thirty-six) samples at the pine plot (MP1). Instances of rapid transmission

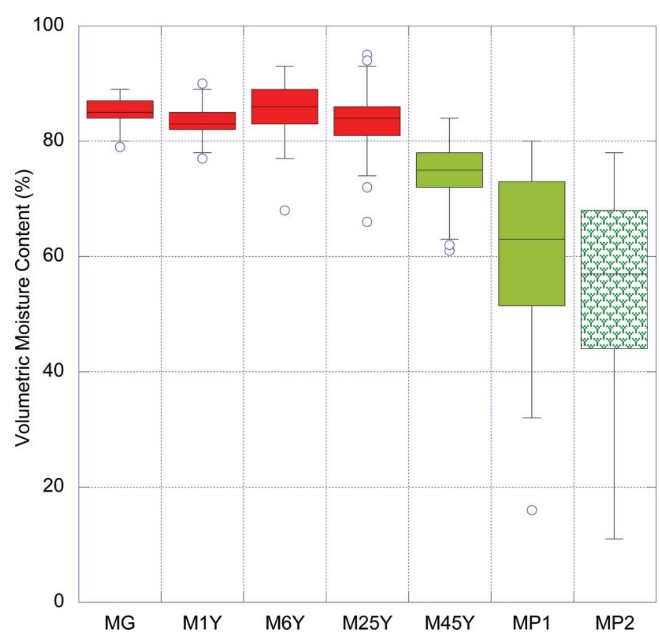

Figure 3. Soil moisture in the upper 12 cm of soil across sites at the Mazar Wildlife Reserve. Red indicates grassland; different shades represent significant differences in volumetric moisture content. (Color figure available online.)

under the pines (e.g., to 20 cm to 40 cm within the first five minutes) signal the presence of preferential pathways, probably along root channels. In the one-year test, bromide concentrations were detected in all plots. At the grassland sites ZB and M6Y the greatest bromide concentrations were at 30 cm to 60 cm depth. At pine site MP1, concentrations inside and outside of the plot increased down the profile to a maximum at the greatest depth sampled (90 cm); however, at pine site ZPine, where roots interfered with sampling, the one sample recovered showed bromide at all three depths tested (0 cm–30 cm, 30 cm–60 cm, and 60 cm–90 cm), with the greatest concentration at 30 cm to 60 cm.

Discussion

Of the land uses evaluated, only afforestation showed significant changes to soil moisture. No significant differences in soil moisture were associated with the frequency of burning, except at site M45Y, where the absence of fire had allowed woody species to colonize. Soil hydrology was not significantly affected by the presence or exclusion of alpaca grazing. Soil moisture at site MG, adjacent to the Mazar Reserve and managed with frequent burning (two- to three-year cycles) for cattle grazing, did not differ from that of other grassland sites (Figure 3).

Properties of páramo soils are similar in these two study areas. A horizons are thicker in the north and particle size is slightly coarser in the south, but textural classes are similar between areas. The relative homogeneity of the soil matrix among sites allows differences in soil moisture and soil water retention capacity to be attributed to differences in land use and management. One difference in soil properties associated with pine plantation appears to be a granular structure of the A1 horizon, in contrast with a strongly to moderately subangular blocky structure at other sites. Because this difference appeared at only two of three pine sites, however, further study will be required to determine whether it is a widespread effect of afforestation in the páramo.

Among Ecuadorian páramos, typically burned every two to three years, the Mazar Wildlife Reserve is unusual because portions of it have not burned for decades. Site M45Y, which had not burned in at least forty-five years, contained successional vegetation and displayed soil moisture values transitional between those of grassland and pine sites. This suggests that woody vegetation will replace páramo grasses where conditions are favorable and that changes to the soil accompany the grassland-to-woody vegetation transition. Changes to the soil occur from the top down. Soil structural differences were observed only in A1 horizons. Below the A1 horizon, soils under pines at the Mazar Reserve retain many properties from their prior state as páramo soils. Analysis of soil humic acids showed that all sites at both study areas have melanic epipedons, expected of grassland soils, rather than fulvic epipedons, expected of forest soils (Neirop et al. 2007; Hartsig 2011).

Results of this study call attention to significant changes to soil–water relations under tree plantations and suggest that the trees *Pinus* and potentially *Polylepis* reduce soil moisture contents and allow less uniform yet rapid movement of soil water. Implications of this are timely and important, as current efforts to plant trees for carbon sequestration or timber production can be expected to decrease the soil water in páramo landscapes. This study affirms, at a regional scale, results of earlier, localized studies by Farley, Kelly, and Hofstede (2004) and Buytaert, Iñiguez, and de Bièvre (2007). In our study, the spatial distribution of soil moisture at sites with pines and 3-m-tall *Polylepis racemosa* trees was more variable than at grassland sites. Different site factors (e.g., distance from the nearest tree, canopy cover, understory vegetation, root patterns, and nonuniform distribution of other biotic and abiotic components) might explain within-site spatial variability of soil moisture under woody plants.

Our field experience at the pine site MP2 demonstrated that perceived moisture in a stand of pines can be unrelated to below-ground conditions. This site appeared moist under the canopy, with abundant, drippy mosses and bryophytes, but its soils were significantly drier than those of grassland sites. Precipitation has not been measured at MP2, but the site appears to receive more fog and less breeze and is slightly lower in elevation than the MP1 pine site. Differences between moisture conditions at the two Mazar Reserve pine plantation sites highlight the importance of site factors other than the trees themselves and the need to obtain data from additional plantations in páramos.

This study is the first to investigate the effects of *Polylepis racemosa* on páramo soils. Soil at site ZAg-P, dominated by large (3-m-tall) *Polylepis racemosa*, was significantly drier than at grassland sites, but smaller *Polylepis* trees (1 m tall, 3 m apart) at other sites did not affect soil moisture, presumably because their root systems are small and their water requirements are low. The unknown legacy effects of potato cultivation at site ZAg-P and the absence of comparable, uncultivated sites with mature *Polylepis* confound attempts to draw conclusions about the hydrologic effect of *Polylepis racemosa* on páramo soils. Because *Polylepis racemosa* is viewed as a favorable alternative for carbon storage in páramo landscapes, further research is warranted to quantify its water use and effects on soil hydrology.

Pines can increase rates of water movement through these soils. After a year, bromide was detected at greater depth in soil at pine compared to grassland sites. Similarly, the two-hour tracer test showed faster movement at some points under pines, although infiltration was more spatially consistent at grassland sites. Differences in soil–water movement can be attributed to differences in roots. Roots of the grasses are relatively uniform, dense, and fine (< 2 mm diameter) and extend through the A horizons. Pine roots are larger, woody, spatially nonuniform, and concentrated in the upper soil profile. An occasional deeper pine root can facilitate rapid movement of water through the soil profile. Patterns of greater water use and coarser roots of trees, compared to grasses, merit further study to improve understanding of the mechanisms by which woody plants affect the hydrology of páramo soils.

Conclusion

This study documented drier soils at afforested sites than at páramo grassland sites and intermediate soil moisture contents at a transitional site. No significant differences in soil moisture were associated with the frequency of burning, except where fire exclusion had allowed woody plants to colonize. Observed differences in soil structure and moisture consistency, as well as tracer tests of water movement through soil profiles, indicate that pine plantation in páramos alters soil properties, decreases soil moisture, and can increase rates of water movement through the soil. With only one *Polylepis racemosa* site studied, the hydrologic effects of that species remain inconclusive. This study confirms trends reported in the emerging literature on páramo hydrology and adds the likelihood that soil properties begin to change rather rapidly, within decades, following conversion from grass páramo to tree plantation or successional woody vegetation.

High soil moisture contents, multiplied by the great depth of the A horizons, account for an important volume of stored water and underscore the need to manage páramos as key contributors and regulators of freshwater resources in the Ecuadorian Andean region. Although afforestation and forest protection projects might improve water supply and water quality in some environments, in this study afforestation was the one land use significantly associated with a decrease in soil moisture. Today, Ecuadorian páramos have the attention of many stakeholders, from local communities to cities, foreign nations seeking places to sequester carbon, and governmental and nongovernmental CES programs. Results of this study suggest that management to promote water-related ecosystem services in páramos should not include tree plantation but could include grazing and burning. Managing the landscape to promote water management, carbon sequestration, and timber production will require accepting trade-offs among these objectives.

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