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Spatio-temporal and cumulative effects of land use-land cover and climate change on two ecosystem services in the Colombian Andes

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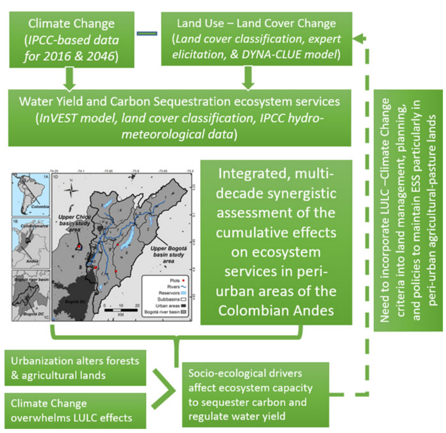
HIGHLIGHTS

- Cumulative climate change and LULC dynamics can have marked effects on ecosystem services.
- We studied such effects on water yield and carbon sequestration in two watersheds in Colombia.
- Climate scenarios had greater effect on water provision than land-use land-cover scenarios.
- Carbon sequestration was greater in forest and shrubland areas farther from Bogota.
- It is key to incorporate climate conditions in land planning for sustainable provision of services.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change can have marked effects on ecosystem service (ES) provision in the Andes, particularly in peri-urban areas. In addition to global-change related processes, cumulative effects such as changing socio-political dynamics, environmental policies, and conflicts are also changing type and magnitude of land use–land cover (LULC) dynamics in the Colombian Andes. Studies in the region have investigated the effects of LULC change, deforestation and extreme climatic events on the hydrology of watersheds and carbon sequestration. Yet, less is known on how the cumulative effects of climate and LULC changes will drive water yield and carbon sequestration. To investigate these cumulative effects, we study two different watersheds near Bogota, Colombia and their ES for the period 2016–2046. We use IPCC-LULC scenarios, expert elicitation, hydro-meteorological data, and integrated modelling using temporal LULC change and ESs valuation models to parse out effects of LULC versus climate change on two representative ESs. Our results show forest and shrublands remain stable during the analysis period. However, urban conversion of agricultural pastures is substantial. We found that climate change scenarios had greater effect on water yield and supply than LULC scenarios in both watersheds. However, carbon sequestration was greater in rural forest and shrubland areas farther from Bogota. In contrast to current land use zoning being promoted by local elected officials, our findings indicate that land-use development and policies in near-urban basins need to minimize urbanization in agriculture and pasture LULCs, as these can have

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substantial effects on water yield. Similarly, land use polices in ex-urban areas need to conserve forested and shrubland areas to maximize their carbon offset potential. Collectively, our results highlight the need to incorporate climate change conditions in decision making and land use planning processes, in order to maintain the capacity of ecosystems, both urban and rural, to provide services to society.

1. Introduction

Several anthropogenic threats affect ecosystems at multiple scales. Environmental change, the combination of multi-scale climate alteration and disturbances on natural and socio-ecosystems, cumulatively act to alter and degrade ecosystem properties. Among these affected properties are ecosystem composition, structure, and function, which support the capacity of ecosystems to provide ecosystems services that benefit humans (Grimm et al., 2013; Sharp et al., 2018). These changes occur at multiple spatial-temporal scales, including large-scale human induced changes in climate that can force large-scale changes that affect ecosystem function and distribution (Fu et al., 2017). Similarly, short-term, local-scale ecosystem disturbances related to land use and their interactions with climate change, can have the potential to affect ecosystem structure and function. For example, agricultural practices in the central Andes of Colombia affect hydrological (García-Leoz et al., 2018) and biogeochemical (Suescún et al., 2017) functions; and the interactions between land use and climate variability exacerbate these effects (Suescún et al., 2019). When considered at larger scales, forest ecosystems are often related to the maintenance of hydrological regulation (Mercado-Bettin et al., 2019) and atmospheric circulation in South America (Molina et al., 2019).

Other socio-economic and ecological factors and disturbances such as changing socio-political dynamics, globalization, land use and environmental policies, and the recent post-conflict process, are also changing both the type and magnitude of land use – land cover (LULC) dynamics in the Colombian Andes, particularly in peri-urban areas (Rubiano et al., 2017; Salazar et al., 2018). For example, in the past few decades agricultural expansion and changing socio-ecological dynamics have historically resulted in deforestation in several regions of the Colombian Andes (Armenteras et al., 2017). This growing agricultural front has resulted in vast deforestation and is mostly related to increased demand for crop and livestock grazing lands (Armenteras et al., 2013). Additionally, recent urbanization trends are characterized by a sizable rural migration to urban areas, such as Bogota and Medellin, the two largest cities in Colombia, and have resulted in significant land use – land cover changes (LUCC), particularly land abandonment with subsequent forest regeneration in these former rural and peri-urban agricultural areas (Mendoza and Etter, 2002). Land speculation, poorly defined land tenure regimes, illicit crops and mining are also major drivers of LUCC in Colombia, especially in regards to loss of forest cover and mercury related water pollution (Dávalos et al., 2011). The dynamics of these cumulative LULC changes also lead to biodiversity and habitat loss, as well as altered biogeochemical cycles (Nelson et al., 2010). Specifically, changes in forest biomass and soil quality can potentially alter carbon dynamics, evapotranspiration, as well as infiltration and water regulation functions (Sharp et al., 2018). As such, cumulative effects will directly affect the capacity of ecosystems to provide key services such as carbon storage and water regulation, which are fundamental in the tropical Andes, where a large portion of the population lives (Bradley et al., 2006; García-Leoz et al., 2018).

There is a large body of literature studying the effects of LULC and climate change on ecosystem structure and subsequent functions and services (Grimm et al., 2013; Fu et al., 2017). Most of these spatially-explicit studies have used a combination of functional models and scenarios to study the effects on forest ecosystem services in association with forest management (Bottalico et al., 2016), urbanization (Delphin et al., 2016) and combined climate-LULC effects (Fu et al., 2017). Scenarios are regularly used in these models and their output can inform management, policy and planning decisions, and climate change adaptation and mitigation strategies (Nelson et al., 2010; Liang et al., 2018a, 2018b). Geospatial methods can also be used to spatialize information related to such scenarios of forest change (Lagrosa et al., 2018; Liang et al., 2017a, 2017b), urbanization (Jiang et al., 2017) and climate change (Jorda-Capdevila et al., 2018).

Previous studies have investigated the effects of LUCC, deforestation, and extreme climatic events on the hydrology of Andean watersheds (Ochoa-Tocachi et al., 2016; Bonnesoeur et al., 2019). However, less known is how the combined effects of tropical forest loss, climate change and urbanization are driving water regulation and biomass in peri-urban Andean watersheds that are fundamental for the provision of key-ecosystem services. Understanding the effects of rapid socio-ecological changes on regulation ecosystem services in the Andes will provide key information for management and conservation goals, as well as the development of climate change related policies, strategies, and incentives. Nevertheless, in the Colombian context, up to date and accurate geospatial data are often unavailable, access to sites is difficult, and land use dynamics are rapidly changing (Rubiano et al., 2017; Etter et al., 2006).

In this study, we explore the cumulative effects of socio-ecological disturbances on two case study watersheds and their ecosystem services in the Colombian Andes. The first larger watershed includes a dynamic urban area with over 8 million inhabitants, while the second is a smaller more rural and peri-urban watershed. Both watershed as such typify land use dynamics in upper Andean areas. Our specific objectives are three-fold. First, we model LUCC in both watersheds during the period of 2016–2046. Second, we estimate changes in water yield and carbon storage, in both watersheds during this same period. Finally, we assess and discuss the overall cumulative effects that forest cover dynamics, climate change, and urbanization will have on these watersheds and the provision of these two key ecosystem services.

2. Materials and methods

Below we describe how we use International Panel on Climate Change (IPCC)-LULC scenarios, expert elicitation, available LULC and hydro-meteorological data, and an integrated modelling approach using the DYNA-CLUE (Verburg and Overmars, 2009) and Integrated Valuation of Ecosystem Services (InVEST; Delphin et al., 2016) models. Such an approach will allow us to assess the cumulative impacts of LULC and climate change on two representative ecosystem services in two study watersheds.

2.1. Study area

The study area is located in the Upper Bogota and Upper Chicú river watersheds, in the eastern Colombian Andes (Fig. 1). Approximately 20% of the study area is in Bogota's high elevation plain characterized by isolated hills and an average elevation of 2600 m.a.s.l., while the remaining area is comprised of about 80% mountains. The high elevation plain has a fluvial-lacustrine origin with slopes of 1–3% and is characterized by flood plains and terraces composed of clastic deposits and volcanic ash mantles. Meanwhile, mountainous areas are comprised of igneous, sedimentary and metamorphic parent material (IGAC, 2000,

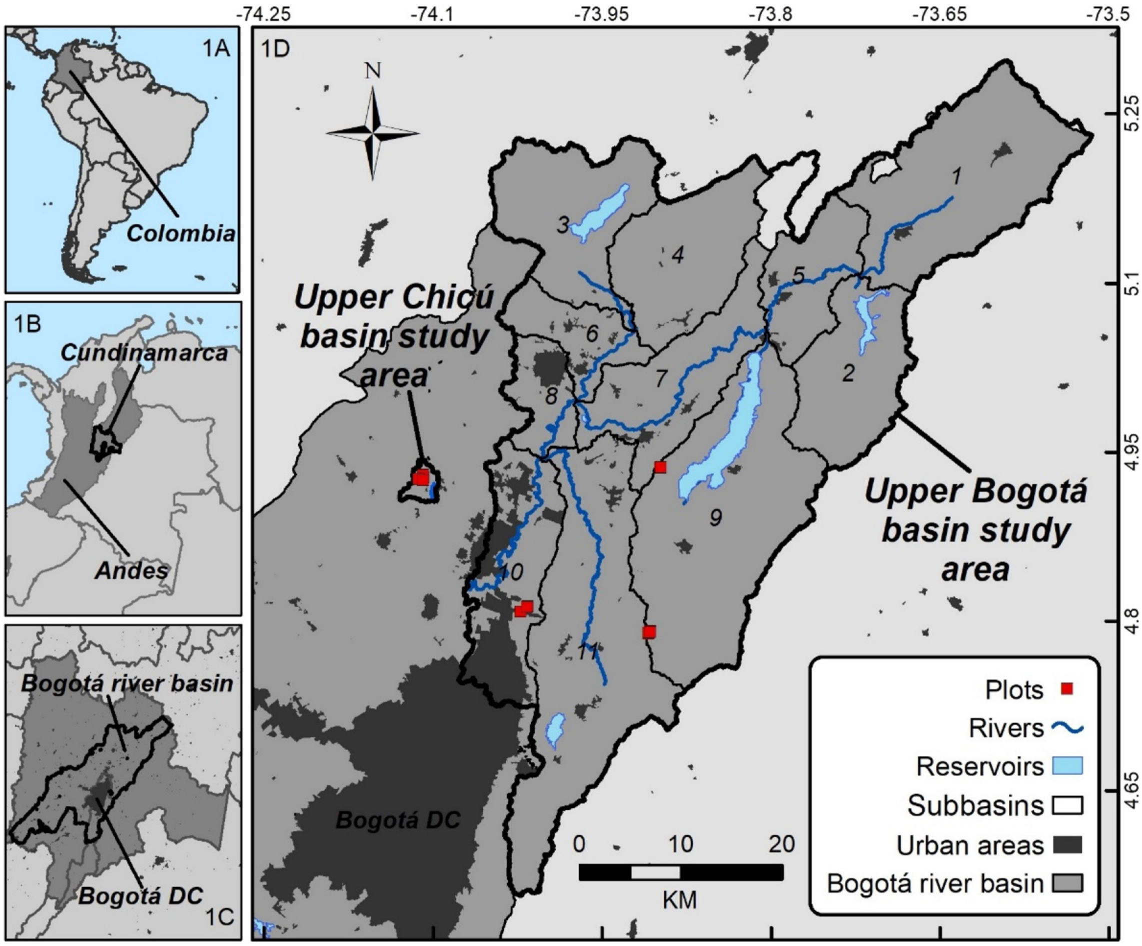

Fig. 1. A) Colombia; B) the Andes mountain range and the Department of Cundinamarca; C) the Bogota river basin, and D) delineation of the study area depicting the upper Bogota basin, including the individually numbered sub-basins, and the upper Chicú basin (bold line). Permanent forest plots used in this study are depicted in red. Geographic Coordinate System WGS 1984. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2017a). Mean annual precipitation varies according to elevation in the study area and ranges from 625 and 1155 mm at 2600 and 3160 m.a.s.l., respectively (IDEAM, 2018; CAR, 2017a). Precipitation is monomodal in the eastern portion of the study area and is greatest mid-year, whereas in the high plain it is bimodal with average maxima from March to May and September to November. Average temperature is 12–14 °C in the high-plain and <10 °C above 3000 m a.s.l. (Pabón, 2011).

The study area is characterized by four biomes: the Cundiboyacense high-plain, Andean azonal orographic, Andean orographic, and Paramo orographic (IDEAM et al., 2017). According to the soil World Reference Base (WRB), soil types in the study watersheds are predominantly Dystric Gleysols in the high elevation plains, while Leptic and Haplic Umbrisols as well as Gelic Cambisols are found in mountainous regions of the eastern study area (Gardi et al., 2015). The Colombian Andean region also has one of the most diverse flora in the world (Moreno et al., 2017). Upper Andean forests in the study area are found mainly above 2700 m.a.s.l. and are dominated by Ericaceae, Myrsinaceae and Asteraceae families and characteristic trees such as *Weinmannia tomentosa* and *Clusia multiflora* and a diversity of bryophytes, lichens and epiphytes. Secondary Andean forests are widespread and present a high percentage of lianas and vines (CAR, 2006). Planted Pinus spp. and Eucalyptus spp. forests are also common in the study area. Other rural and urban LULCs are discussed in Section 2.3.

The upper Bogota river watershed is one of the most historically anthropogenically disturbed regions in the Northern Andes (Van der Hammen, 1998), has a population of over 8 million, and is home to a large part of the nation's economic activities (CAR, 2017b). The region is an important agro-industrial center with flower growing industries, dairy farming, livestock and mining activities (Antonio-Fragala and Obregón-Neira, 2011). Historically, the study area lost most of its original forest vegetation (Van der Hammen, 1998), and the region is currently dominated by exotic trees planted in past reforestation programs in the 1960s (Mendoza and Etter, 2002). The area's increasing demand for water has resulted in several regulation and catchment systems, including the 440.3 Mm^3 project that transfers water from the Orinoco basin to the study area; resulting in regional hydrologic cycles being substantially altered (IDEAM, 2015).

2.2. Watershed delineation

We delineated the study watersheds using the ArcSWAT© program based on: a 1 arc-second (~30 m) resolution Digital Elevation Model (JAXA-EORC, 2017), the location of hydrologic station outlets (CAR, 2017a), and 1:100,000 scale drainage network data (IGAC, 2017b). The watersheds included 14 permanent monitoring plots located in upper Andean forests that were used for subsequent parameterization of models (Rubiano et al., 2017; Fig. 1). The upper Bogota study watershed comprises 11 sub-basins (Fig. 1D) with an area of 212,165 ha. The watershed ranges from 2460 to 3780 m.a.s.l. and has a mean slope of 6% in the plains and 24% in the mountainous areas. The 930.3 ha upper Chicú watershed is located west of the upper Bogota watershed and ranges from 2536 to 3160 m a.s.l., with a mean slope of 29%. Due to its reduced size no sub-basins were here delineated.

2.3. Land cover-land use classification

The LULC information was obtained using a supervised classification of two Sentinel-2A satellite images acquired on January 10th, 2016 (dry season) with a cloud coverage of 15% and 19% (ESA, 2015). Sentinel 2 MSI images has 13 bands ranging from Visible (VIS) to Short Wave Infra-Red (SWIR). Their spatial resolution is of 10 m in 4 bands (VIS and Near Infra-Red – NIR), 20 m in 6 bands (Vegetation Red Edge – VRE–, NIR and SWIR) and 60 m in the 3 atmospheric bands (coastal aerosol, water vapor and SWIR cirrus). Images were processed to the 1C level, and included geometric, atmospheric corrections, orthorectification and projection with *Top of Atmosphere* (TOA) reflectance values (ESA, 2015). Images were also preprocessed to obtain reflectance values at the ground surface level (*Bottom of Atmosphere* – BOA) using the SNAP Toolbox© and the Sen2Cor© processor and additional topographic corrections with a higher resolution DEM, atmospheric and cirrus clouds detection (ESA, 2017).

The final 20 m resolution images with *BOA* reflectance values were used as input in a supervised classification with a minimum distance algorithm to obtain a LULC thematic map. The following LULC typologies were identified in the study area: forests, water bodies, agricultural area, grasslands, agricultural pastures, shrublands, urban area and degraded area. Agricultural pastures refer to land where temporary pastures are alternated with crops. The training samples for classification were defined using high resolution historical imagery and digitized on screen using Google Earth®. The classification accuracy was performed using 50 random points per LULC using the same high resolution historical imagery used for the ground trothing process (Tilahun and Teferie, 2015).

2.4. Land cover land use scenario

We modelled LULC over 30 years (2016–2046) using the spatially explicit Dyna-CLUE model (Conversion of Land Use and its Effects; Verburg and Overmars, 2009). Several approaches used to model LULC such as CA-Markov, have been applied in analyses of ecosystem services (e.g. Hamad et al., 2018; Liang et al., 2017a, 2017b). However, we opted for Dyna-CLUE because of several advantages: 1) a simplified structure and easy parametrization, 2) a capacity to simulate LULC changes and local processes interactions through the implementation of both top-down and bottom-up modelling approaches (Ren et al., 2019), and 3) it is widely reported in the scientific literature. The model spatially simulates land use dynamics based on empirical relationships between biophysical and socio-economical LUCC drivers and has been used at both national and continental scales with spatial resolutions over 1 km (Verburg et al., 2008) and at regional scales (Verburg et al., 2002). The Dyna-CLUE version used for this analysis first identifies changes in every land use class and then allocates the changes spatially according to location characteristics and land use probability present within a pixel (Verburg, 2010). For specific details and methods on model parameterization including: spatial policies and restrictions, conversion settings, land use requirements/demands/characteristics, and regressions for estimating pixel change, refer to Supplementary Material A.

This Dyna-CLUE version requires conversion elasticities and transition sequences, which were estimated using expert elicitation. Specifically, we used an on-line Google Forms® instrument and surveyed a total of 12 local landscape ecologists ($n = 3$), forest ecologists ($n = 3$), planners and land managers ($n = 4$) and geospatial analysts ($n = 2$) familiar with the land use dynamics in the study watersheds. Land use requirements for the modelled years (2016–2046) were obtained using trend extrapolation of LULC changes during 2002 to 2012 based on CORINE Land Cover (CLC) datasets at 1:100.000 scale. The CORINE methodology for Colombia adopts land cover classes similar to the European CORINE scheme and is regularly used by the governmental Institute of Hydrology, Meteorology and Environmental Studies –IDEAM- to derive official LULC statistics for the country(IDEAM, 2010). The CLC legend was first reclassified and made consistent with our LULC classification scheme and a probability transition matrix was derived from 2002 and 2012 CLC data. A Markov Chains approach using 10 years of reference data was then applied to our study LULC areas for years 2026, 2036, and 2046 using our 2016 LULC map as a baseline and the probability transition matrix (Kumar et al., 2014). Drivers of LULC change were selected from the available literature and tested as predicting variables (Table 1). Only significant predictors ($p < 0.001$) were included in the Dyna-CLUE model runs.

The Dyna-CLUE model parametrization was based on a business-as-usual scenario that assumes projected land use changes follow trends from previous years, while other factors were kept constant (Radeloff et al., 2012; described in Supplementary Material A). The 2046 projected LULC map was used as our future scenario in the following section on modelling water provision and carbon storage ecosystem services. The Dyna-CLUE model has previously been used and integrated with the InVEST model to assess the potential LUCC effects on ecosystem service provision, (e.g. Jiang et al., 2017; Liang et al., 2017a, 2017b).

2.5. Ecosystem services modelling

2.5.1. Water provision

Water provision was modelled as water yield in the watersheds using InVEST's annual water balance model (Sharp et al., 2018). The water balance baseline scenario was produced for year 2016, while the cumulative effects scenario was simulated for year 2046. The model estimates the relative contributions of water from each sub-basin of a study watershed, runs on a gridded map and calculates the amount of water runoff (i.e., yield) from each pixel or the precipitation less the fraction of water evapotranspiration. It then subtracts water consumption to obtain the realized water supply at the watershed level (Sharp et al., 2018). The model requires data on average annual precipitation, reference evapotranspiration (ET_o), a crop evapotranspiration coefficient (Kc), root depth, soil depth, plant available water content (AWC) and consumptive water use per LULC class. For specific detail on parameterization methods for the InVEST annual water balance model, please see Supplementary Material B.

We estimated water consumptive use for each of the main sectors and associated them to the most representative LULC class. We define water consumptive use as the *water footprint*, or "the volume of water

Table 1
Relevant land use change driving factors identified for the upper Bogota and Chicú study watersheds in Colombia.

Driving factor	Data source	Reference
Soil fertility	Colombia Soil Map, scale 1:100.000 (IGAC, 2017a)	Rubiano et al. (2017)
Euclidean distance to roads	National base cartography at 1:100.000 scale: Roads (IGAC, 2017b)	Etter et al. (2006); Rubiano et al. (2017)
Euclidean distance to urban centers	Colombian National Geostatistical Framework 2016 (DANE, 2017)	Delphin et al. (2016); Lambin et al. (2003); Rubiano et al. (2017)
Euclidean distance to water lines	National base cartography at 1:100.000 scale: Major and minor drainages (IGAC, 2017b)	Anselm et al. (2018)
Elevation	ASTER Global Digital Elevation Model v.2 (Tachikawa et al., 2011)	Anselm et al. (2018)
Slope	ASTER Global Digital Elevation Model v.2 (Tachikawa et al., 2011)	Anselm et al. (2018); Armenteras et al. (2013); Rubiano et al. (2017)
Aspect	ASTER Global Digital Elevation Model v.2 (Tachikawa et al., 2011)	Anselm et al. (2018)

used for anthropogenic purposes that does not return to the watershed where it was extracted from or returns with a quality that does not permit its reuse" (IDEAM, 2015). Consumption by the agricultural area class was estimated by multiplying the average crop yield (ton/ha) reported by DANE (2017) by the mean blue water footprint (m^3/ton) reported by Mekonen and Hoekstra (2011) for potatoes, the dominant crop in the study area (DANE, 2017). Water use by cattle ("Agricultural pastures" LULC) was estimated using livestock carrying capacity (animals/ha) reported by Fedegan-FNG (2014) and mean consumption values per animal reported by Mekonen and Hoekstra (2012). Industrial water use was assigned to the urban LULC class and for the upper Bogota watershed was calculated as the blue water footprint reported by CTA et al. (2015). For the upper Chicú basin, in the absence of a reported value, we used the water demand described by CAR (2006) for the whole watershed and multiplied it by the proportion occupied by the study area. Finally, domestic water was estimated using the standard daily supply for human consumption per capita (IDEAM, 2015) and number of inhabitants per municipality (DANE, 2017). We separated consumption in rural (i.e., agricultural area, agricultural pastures) and urban areas based on the distribution of urban-rural population at the municipal level.

To derive an indication of the model performance, we compared the simulated annual realized supply with the recorded annual mean flow at each of the two outlets for the period 2012–2017. The upper Bogota watershed's realized supply was 93.5% of the recorded yield, while for the upper Chicú's was equal to 78% (Supplementary Material C). For scenario simulations we first obtained a baseline water balance employing precipitation and ET_o grids estimated for 2016. We then used two climate change scenarios for the year 2046; our precipitation and ET_o variable grids were based on projected monthly precipitation and maximum and minimum temperatures from the Third National Communication on Climate Change for Colombia (IDEAM et al., 2015). Specifically, for our three scenarios we used a monthly temporal scale and a multi-model ensemble for the Representative Concentration Paths (RCP) 2.6 ("Peak And Decline", PAD hereafter) and RCP 8.5 ("Business As Usual", BAU hereafter) to represent the extreme climate change scenarios within which precipitation and *ETo* can be expected to vary during the analysis period. In doing so we use these three scenarios to identify the effects of climate change, urbanization and forest cover change, among other drivers (i.e., cumulative effects), on ecosystem services during our analysis period. We isolated the LULC change effects at the sub-basin level by calculating the coefficient of determination between water yield and changes in LULC area at the sub-basin level.

2.5.2. Carbon storage modelling

Using methods outlined in Sharp et al. (2018), we estimated LULC level carbon storage using the InVEST© Carbon Storage and Sequestration model according to three pools: aboveground, belowground, and dead biomass. Using data from 14 permanent forest plots and a literature review, we estimated carbon stocks for all 3 pools and used their sum as the metric for net carbon storage for our 2016 baseline year and its net change (i.e., sequestration or emissions as defined in this study) over the analysis period to year 2046 (Table 2). The soil carbon pool was excluded from our analysis because our aim was to assess the cumulative effects on LULCs and their aboveground ecosystem dynamics. Also, aboveground pools are more frequently reported in the relevant literature (see Alvarez et al., 2012; Clerici et al., 2016 and citation therein). We did estimate soil carbon stocks using average percent soil organic matter, bulk density and depth from available data for the entire soil profiles for various LULCs. But, estimates were substantially greater than the sum of the other 3 pools, thereby masking the effects on aboveground LULC dynamics and making discussions relative to the literature more difficult.

Accordingly, changes in carbon stocks were estimated using the 2016 baseline LULC and the projected 2046 LULC layer as the future scenario. Biomass values were associated to each LULC class using scientific literature (sources in Table 2). We then converted vegetation biomass to carbon storage using an approximate factor of 0.5 to account for the different biomass types in the study area, a ratio widely used in both the scientific literature and for carbon offset protocols. Forest LULC biomass and carbon were based on the plot-level estimates for the upper Andean forest type; since it was not possible to differentiate Pine/Eucalypt plantations in LULC classification, and given their presence in the study area, their biomass values -from literature- were averaged with those of forests. All operations were carried out using map algebra in ArcGIS®.

Table 2
Data sources used for estimating biomass and carbon stocks in three pools for each relevant vegetation cover in the Upper Bogota and Chicú study watersheds in Colombia.

	Pool	Data source
Forest	Aboveground biomass	Estimated within this study permanent plots
Forest	Dead biomass	Navarrete et al. (2011)
Forest	Belowground biomass	Orrego and Del Valle (2001)
Pine/Eucalyptus	Aboveground biomass	Loaiza-Usuga et al. (2010)
Pine/Eucalyptus	Dead and belowground biomass	Gutiérrez-Vélez and Lopera-Arango (2001)
Shrubland	Aboveground biomass	Estimated within this study permanent plots
Shrubland	Dead biomass	Orrego and Del Valle (2001)
Shrubland	Belowground biomass	Mokany et al. (2006)
Grassland (paramo)	Aboveground, dead, and belowground biomass	Cardozo and Schnetter (1976)
Pastures	Aboveground biomass	Apraez et al. (2007)
Pastures	Belowground biomass	Mokany et al. (2006)
Crops (potato)	Aboveground biomass	DANE (2017)
Crops (potato)	Belowground biomass	Mokany et al. (2006)

3. Results

3.1. Land-use land cover change

The Overall Accuracy for the 2016 LULC classification was 84%, User Accuracy (UA) ranged from 64% to 100%, and Producer Accuracy (PA) ranged from 65% to 98%. Thus, the two thematic maps for years 2016 and 2046 were used to estimate net LUCC through the analyzed period (Fig. 2). The urban area class encompasses only 7% of the study area in 2016 but is estimated to experience the greatest net gain during the analysis period (89%). Conversely, forests and shrublands decreased by 26% and 8%, respectively, but remain relatively stable in terms of the percent of total study area during 2016 and 2046. However, Agricultural area that encompasses 21% of the total study area decreased by 78%, being the LULC class that experienced the greatest net loss (Table 3).

3.2. Water provision

In both watersheds, the largest flux in the overall water budget, as expected was Actual Evapotranspiration (AET), comprising more than two thirds of the precipitation. The remaining share was water yield (WYLD), of which about 30% is consumptively used and 70% moves as streamflow and becomes potential water yield in the upper Bogota watershed; while 20% is consumed and 80% is WYLD in the upper Chicú. Fig. 3 shows the spatial distribution of WYLD for the year 2016 and the annual water balance for both study watersheds. Water balance changes relative to 2016 LULC show that precipitation will increase as expected under a PAD scenario (RCP 2.6) but decrease in a BAU scenario (RCP 8.5) in the upper Bogota, while it decreases under both RCPs for the Upper Chicú. Overall, the Upper Chicú basin shows greater change by reducing incoming water by almost 15% in the BAU scenario. Actual Evapotranspiration share increases in all future scenarios for both watersheds with 77.3% in the Upper Bogota and 84.7% in the Upper Chicú. Accordingly, water yield decreases under all scenarios, while

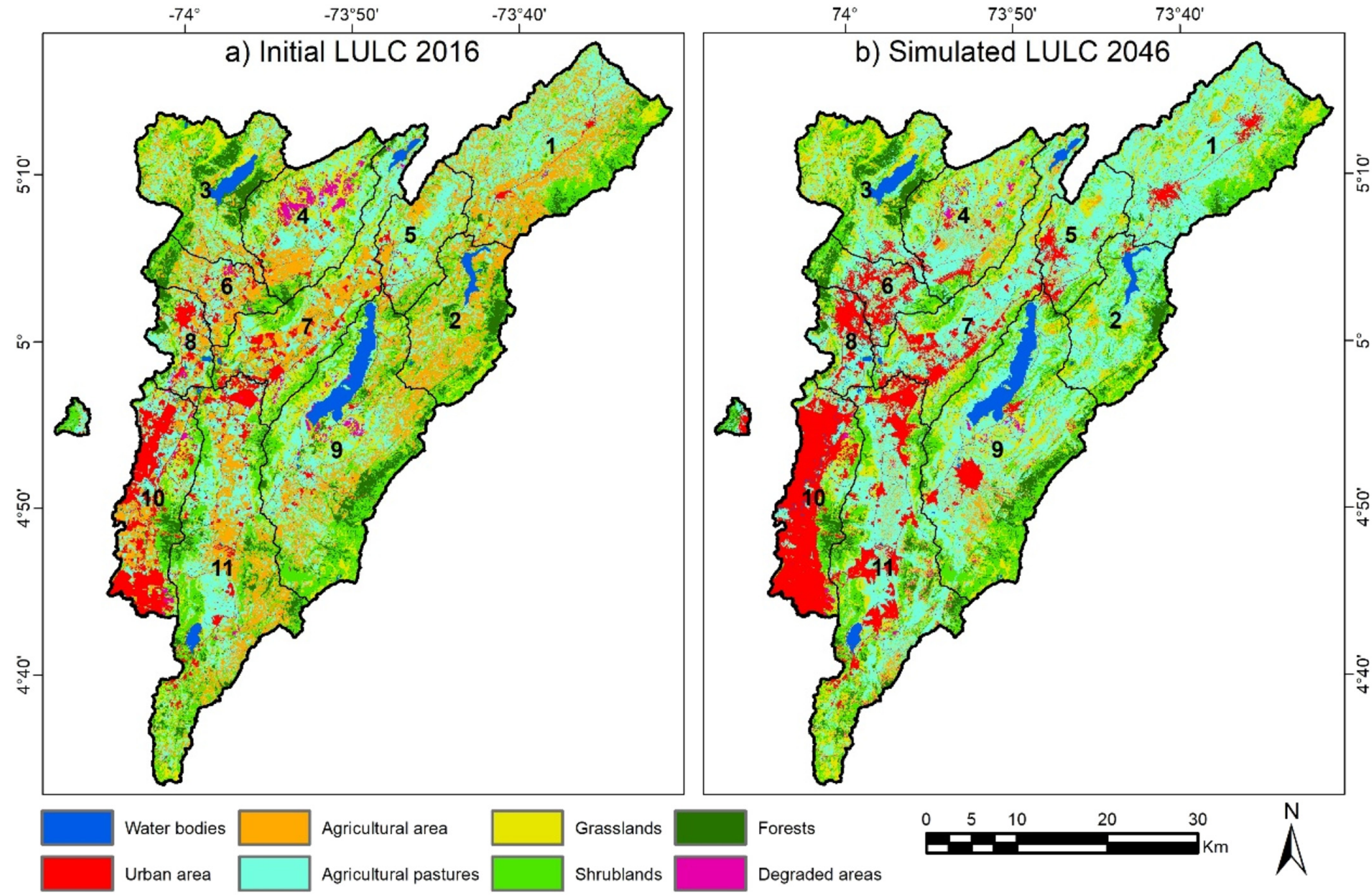

Fig. 2. Land use Land Cover (LULC) maps of the study area. A) 2016 LULC map, classified from Sentinel-2A imagery. B) 2046 simulated LULC map through Dyna-CLUE modelling approach. Black polygons: sub-basins individually numbered. Geographic Coordinate System WGS 84.

2016BAU generates the largest reductions in both basins; up to 17.7% in upper Bogota and 41.9% in upper Chicú. Table 4 shows changes in water balance for both watersheds with respect to the 2016 base line scenario, while Fig. 4 shows spatial changes in water yield using both scenarios.

According to our projected LULC changes, consumed water volume would increase by 11% in Upper Bogota, representing a larger share of the water yield at 39.4% under the BAU scenario. Consumed water volume in the Upper Chicú would in turn drop by 3.4%. This reduction would nevertheless represent an increase in consumed share with respect to the base 2016 scenario because of reduction in the yield. In both basins reductions in water yields and increases in consumed shares would result in less remaining water (supply); specifically, −30% in upper Bogota (204BAU) and −53% in upper Chicú (2016BAU).

Coefficients of determination between water yield and changes in LULC area at the sub-basin level showed for urban areas $r^2 = 0.86$ and $r^2 = 0.8$ for RCP 2.6 and 8.5, respectively, while agricultural pastures had $r^2 = 0.74$ and $r^2 = 0.76$ for the same scenarios, while other LULCs were equal to or below 0.3. As such, we can infer that LULC changes effects on water provision in the Upper Bogota basin might be primarily caused by the urbanization conversion of agricultural pastures within the same climate change projections. In the case of Upper Chicú, water yield increased from 2016 to 2046 by 5.7% with RCP 2.6 (8.2 mm) and 2.4% (3.0 mm) with RCP 8.5. Relative differences (%) were slight at the watershed level but noticeably higher in some sub-basins (e.g. 4 and 10; Table 5). Overall, RCP 2.6 generated higher increments and RCP 8.5 higher reductions. In general terms, RCP scenarios had larger effects on water yield than did the LULC/RCP scenarios.

Table 3
Changes in LULC class (hectares; ha) for baseline year 2016 and the 2046 land use land cover (LULC) scenario.

LULC class	2016		2046		Net change
	Area (ha)	% of total study area	Area (ha)	% of total study area	
Water bodies	5491.0	2.6%	5491.0	2.6%	0.0%
Urban area	14,536.8	6.8%	27,426.1	12.9%	88.7%
Agricultural area	45,534.2	21.4%	10,214.7	4.8%	−77.6%
Agricultural pastures	58,186.2	27.3%	82,598.9	38.8%	42.0%
Grasslands	30,348.4	14.2%	36,305.8	17.0%	19.6%
Shrublands	41,127.9	19.3%	37,997.2	17.8%	−7.6%
Forests	15,256.5	7.2%	11,369.4	5.3%	−25.5%
Degraded areas	2520.2	1.2%	1597.9	0.8%	−36.6%
Total	213,001.0		213,001.0		

3.3. Carbon storage

Total 2016 carbon stocks for the Upper Bogota and Chicú watersheds were 7,675,201.7 Mg C (average of 36 Mg C ha^{-1}) and 51,303.11 Mg C (average of 55 Mg C ha^{-1}), respectively. The Upper Bogota watershed lost or emitted 1,518,921.4 Mg C (−19.8%), while the Upper Chicú sequestered an overall 5963.1 Mg C (+11.6%) during our analysis period. Fig. 5 shows the notable loss in carbon stocks in the Upper Bogota watershed versus areas of noticeable sequestration, primarily in Forest and Shrubland LULCs in the Upper Chicú. Indeed, in the Upper Bogota watershed, none of the sub-basins sequestered carbon over the analysis period (detailed in Supplementary Material D). Overall, changes in the

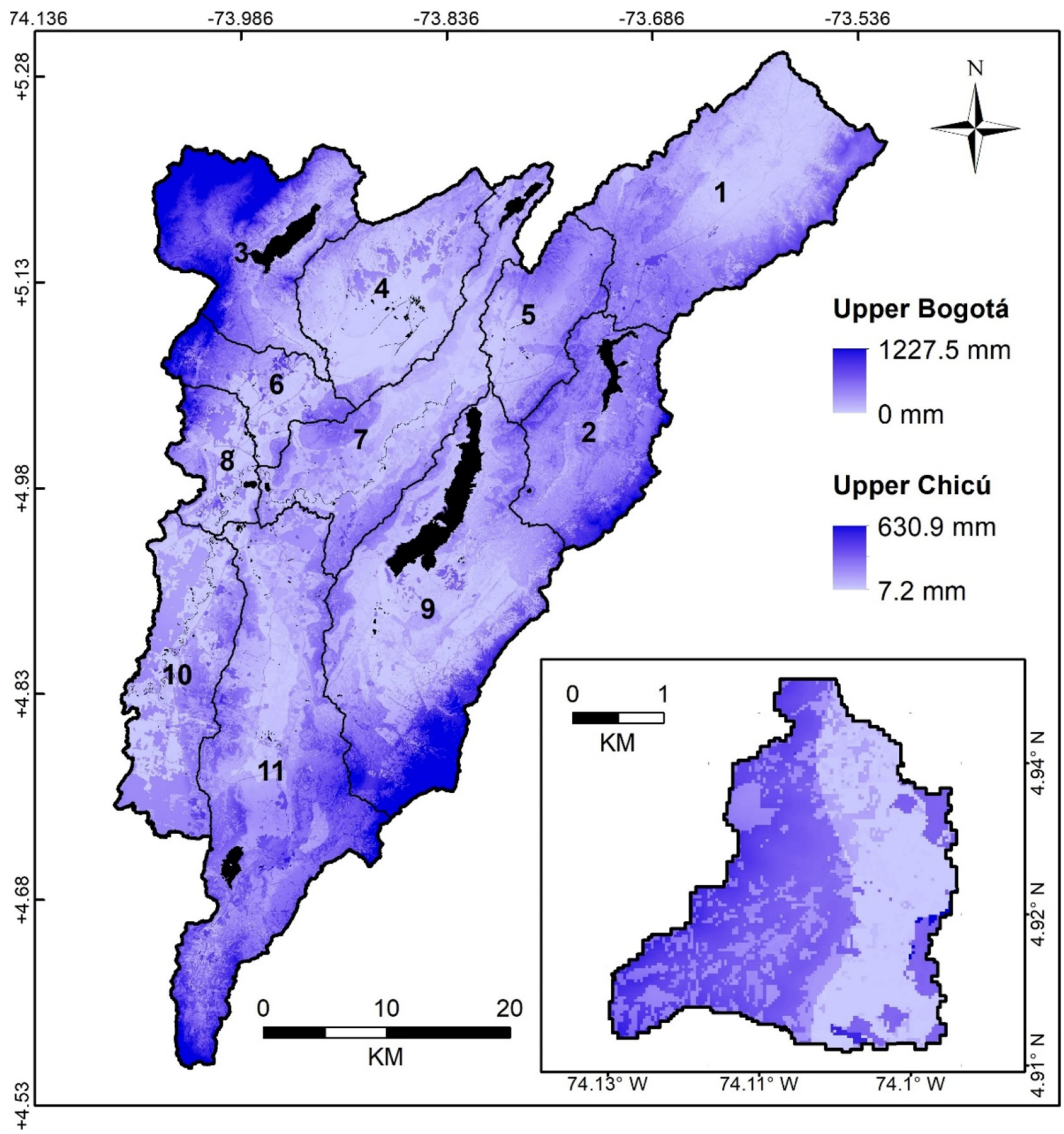

Fig. 3. Spatial distribution for water yield for the year 2016 for the Upper Bogota and Upper Chicú study watersheds in Colombia. Geographic Coordinate System WGS 1984.

Forests and Shrubland LULC are contributing the most to carbon stocks, as evidenced by the coefficient of determination found between the loss in their area and loss in carbon stocks per sub-basin, i.e. $r^2 = 0.69$ and $r^2 = 0.75$, respectively (Fig. 5).

Table 4
Changes in water balance in the Upper Bogota and Upper Chicú watersheds with respect to the 2016 base line scenario. Note: Precip is Precipitation, AET is annual evapotransporation, and WYLD is water yield.

Basin	Scenario name	Component				
		Precipitation (%)	AET (%)	WYLD (%)	Use (%)	Supply (%)
Upper Bogota	2016PAD	+2.3	+4.5	−3.7	0.0	−5.3
	2016BAU	−1.2	+5.0	−17.7	0.0	−25.8
	2046PAD	+2.3	+3.8	−1.6	+11.3	−7.4
	2046BAU	−1.2	+4.4	−16.4	+11.3	−28.9
Upper Chicú	2016PAD	−12.8	−6.9	−33.33	0.0	−42.1
	2016BAU	−14.9	−7.1	−41.9	0.0	−52.9
	2046PAD	−12.8	−7.9	−29.5	−3.4	−36.4
	2046BAU	−14.9	−7.5	−40.5	−3.4	−50.3

4. Discussion

The integrated modelling approach used in this study estimated changes in two key ecosystem services across space and time in a highly complex mountainous area in the Andes. Using both models along with local hydro-meteorological, IPCC, and LULC data, we were able to explore the effects of cumulative socio-ecological changes in two disparate watersheds and their ecosystem services in the Colombian Andes during 2016–2046. Overall, we found that forests and shrublands would slightly decrease during this period. However, urban conversion of agricultural pastures will be substantial. In terms of watershed-level ecosystem services during 2016–2046, we found that climate change scenarios had a greater effect on water yield and supply than LULC scenarios in both watersheds. However, carbon sequestration was greater in more rural forest and shrubland areas further from Bogota. Below we discuss in more detail such cumulative and separate effects of LULC and climate change on water provision and carbon sequestration in both watersheds.

Overall, our 2016–2046 LULC changes show increased urbanization across both watersheds (Fig. 2). This trend is likely the result of increased socio-economic growth that has been historically observed in

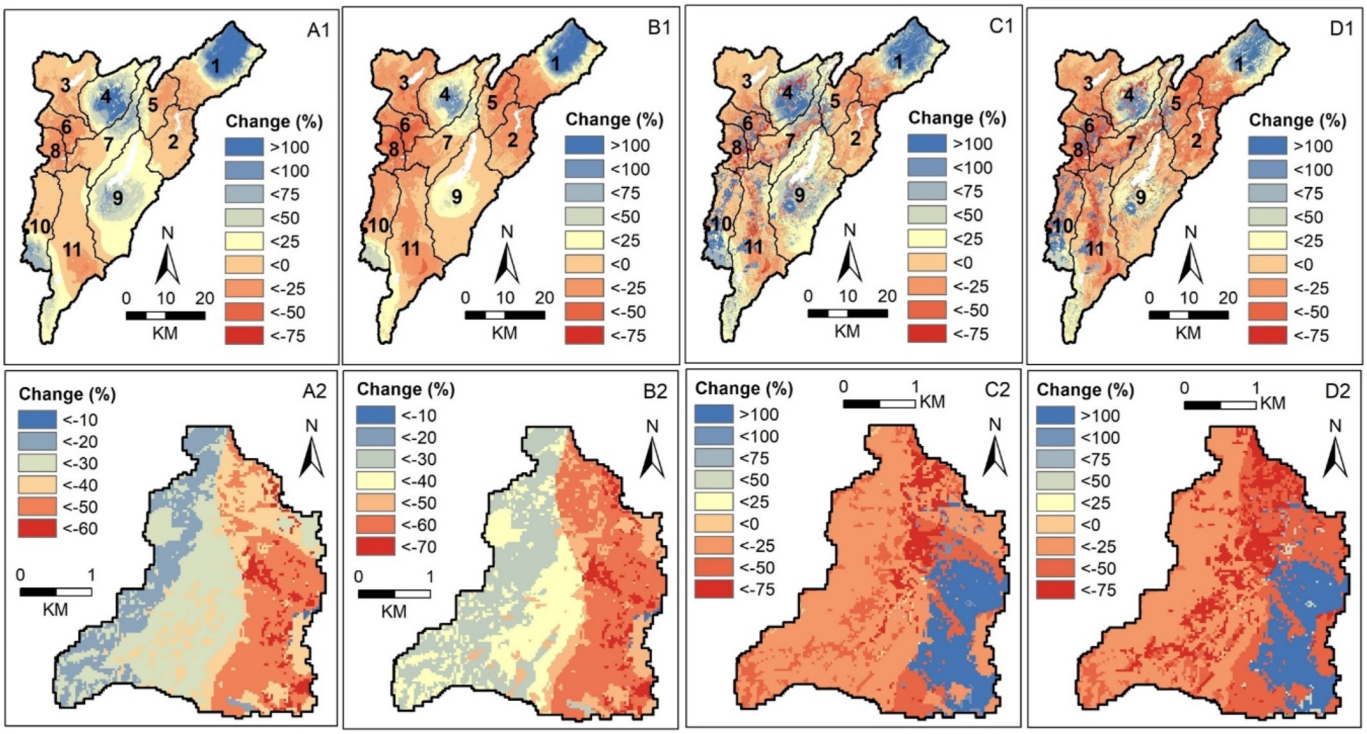

Fig. 4. Changes in water yield for 2016–2046 with Peak and Decline (PAD) and Business as Usual (BAU) scenarios for the Upper Bogota and Upper Chicú watersheds in Colombia: 1 = Upper Bogota, 2 = Upper Chicú, A = 2016PAD, B = 2016BAU, C = 2046PAD, D = 2046BAU.

Bogota and other regions of Latin America (Aide and Grau, 2004). Similarly, the noticeable reduction in agricultural area and associated loss of soil productivity has been observed in the study area by Etter et al. (2008). Our watershed level estimates for forests and shrublands cover during 2016–2046 show only a slight loss across the study areas (Table 3). Rubiano et al. (2017) found in the northern Bogota region for years 1985–2015 a trend of woody vegetation regrowth; the authors suggest this is especially evident when considering high altitudinal belts. In the present study, however, a large part of the area analyzed is lowland and highly urbanized.

Mean annual precipitation showed reductions in relation to 2016 in 3 of the 4 cases (two RCP/two basins), including a small reduction with RCP 8.5 for the Upper Bogota basin and a stronger one (>12%) with both RCPs in the Upper Chicú. Such projected changes in the study area are similar to Pabón's (2011) national and regional scale estimates, but different from the increase reported by IDEAM et al. (2015) for the average scenario projected with the multi-model ensemble for both study areas. Our AET estimates (Table 4) were higher than those reported e.g. by Jujnovsky et al. (2012) and Caro-Borrero et al. (2015) who used the Soil Water Assessment Tool (SWAT) in peri-urban watersheds in near Mexico City. However, Lüke and Hack (2018) caution against making direct comparisons between InVEST and SWAT since both models use different conceptual approaches to estimating the required precipitation, soil water content, water flow, and evapotranspiration parameters when modelling water yield. Similarly, CAR's (2006) evapotranspiration map shows generally lower values than the ones we obtained for the Upper Bogota watershed. In general, ET_o increased in the Upper Bogota watershed but decreased in the Upper Chicú, primarily as a result of variations in precipitation and temperature (Table 4). Maximum and mean temperatures exhibited an increasing trend in two of the three stations used in our interpolation and exhibited the highest values under the RCP 8.5 scenario. This finding is in-line with regional multi-model, multi-scenario averages reported by IDEAM et al. (2015) for the study area and by Anderson et al. (2011) for the Tropical Andes. However, the noticeable reduction of rainfall in the Upper Chicú has an overall greater effect than increased temperature.

In terms of ecosystem services, water yield clearly decreased in both watersheds in response to RCP scenarios as expected due to the effect of climate (Table 4 and Fig. 4). In the Upper Bogota, water yield was primarily due to increased AET, while in the Upper Chicú, this was a result of a strong decay in precipitation that was not compensated by reduced evapotranspiration. Decreased water yield findings for both our watersheds differ from the ones reported by Tapasco et al. (2015) for three Andean watersheds in Colombia, but are within ranges of Anderson et al. (2011). Overall, water yield changes are primarily a result of urbanization of agriculture and pasture-dominated LULCs and where the increased human and industrial consumption would not fully compensate the reduction associated to the loss of agricultural area.

A comparative assessment of our 2016 LULC/RCP relative to the 2046/RCP scenarios shows that 2016 LULC/RCP resulted in larger

Table 5
Differences in water yield between 2016 and 2046 Land Use Land Cover scenarios using both Representative Concentration Paths (RCP) climate scenarios. Sub-basins are spatially represented in Fig. 1.

Climate scenario	Difference	Sub-basin											Total
		1	2	3	4	5	6	7	8	9	10	11	
RCP 2.6	mm	−7.3	−12.7	6.2	−13.4	2.1	20.7	−2.1	11.8	−0.7	48.4	16.4	5.0
	%	−3.6	−4.6	1.6	−12.3	1.2	9.3	−1.5	8.8	−0.3	27.5	6.0	2.2%
RCP 8.5	mm	−7.4	−12.4	5.7	−12.9	−0.7	14.7	−2.8	8.0	−1.1	37.9	14.5	3.2
	%	−4.5	−5.4	1.7	−14.4	−0.5	7.6	−2.3	7.2	−0.5	25.7	6.0	1.7%

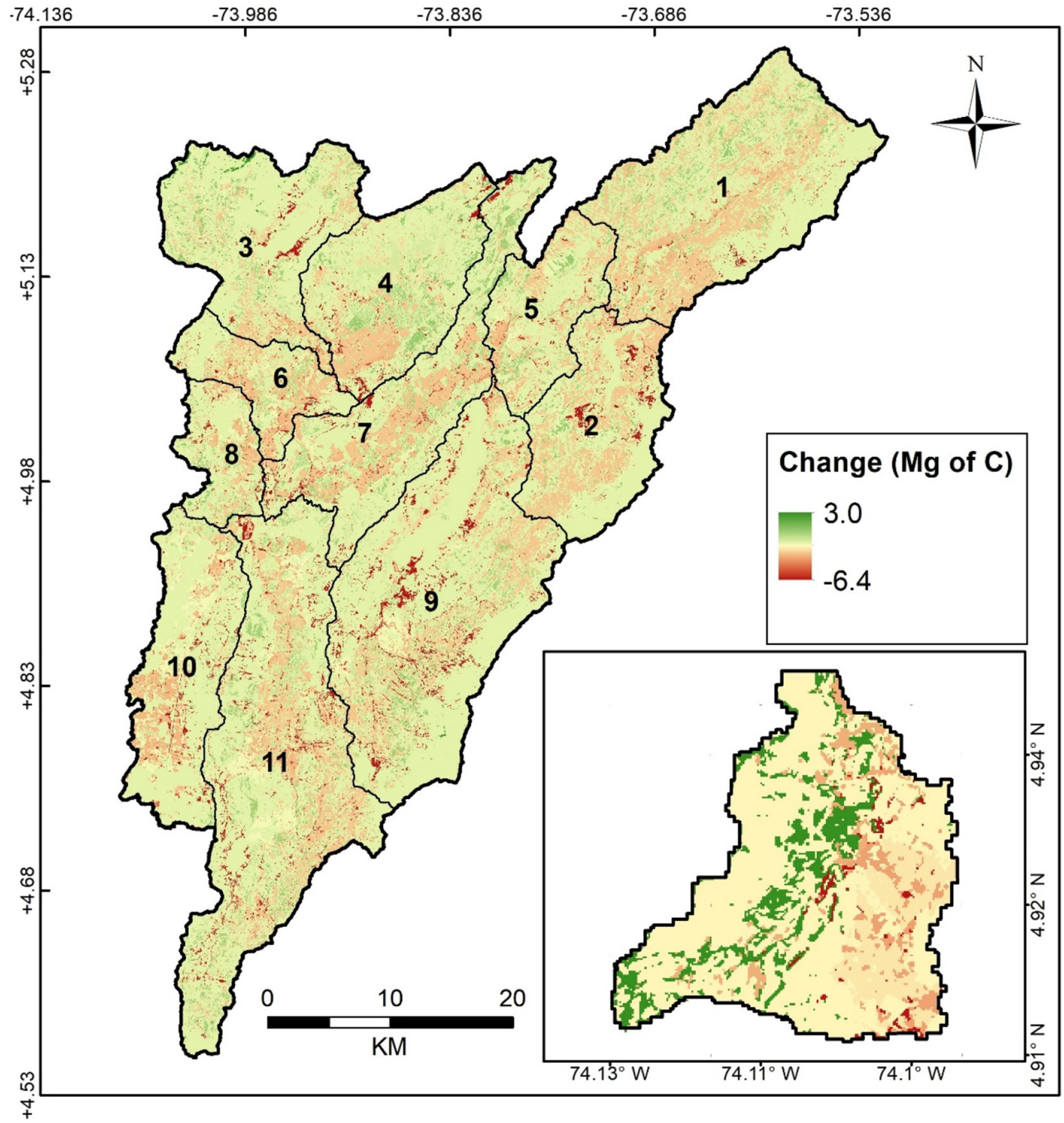

Fig. 5. Carbon stock changes between 2016 and 2046 in the Upper Bogota and Upper Chicú (lower right) watersheds in Colombia. Geographic Coordinate System WGS 1984.

changes on water yield and realized supply in the Upper Chicú watershed, but only on water yield in the case of Upper Bogota (Table 5). Furthermore, accounting for the variation caused by the incorporation of the 2046 LULC scenarios with respect to the 2016/RCP scenarios, we can infer that the latter group is having greater, overall effects on water yield and supply than the first one, a finding similar to those found in Hoyer and Chang (2014).

On the other hand, projected LULC changes up to 2046 suggest noticeable effects on carbon storage and sequestration (Supplementary Material D). Changes in the Forests and Shrubland LULC were contributing the most to carbon stocks (Fig. 5). Other studies such as Delphin et al. (2016) found similar effects of LULC change on carbon stocks, specifically that carbon storage in two Florida, USA watersheds was reduced as a result of urbanization and associated forest cover loss. Similarly, recovery of forest cover in the Atlantic Forest region in Brazil would result in a carbon stock increase (Alarcon et al., 2015). Our average C stock estimates for both watersheds (36 and 55 Mg C ha^{-1}) were within the upper range of those reported in Clerici et al. (2016) (6–50 Mg C ha^{-1}) for upper Andean shrub lands and secondary forests in the study area.

Our modelling results suggest that climate change would be characterized by increasing temperature coupled with reduced precipitation; assuming that economic development and land use policies continue as in the past decades (BAU scenario: RCP 8.5). Such a scenario implies increased urbanization, mostly at the expense of pasture-cultivated areas and forest cover to a lesser degree. There might however be opposite trends at the local scale, associated with the recovery of shrubland and forest LULCs in specific sub-basins. Overall, our modelled LULC changes indicate net carbon emissions and reduced carbon storage capacity through the analyzed period (Fig. 5). Also, urbanization will likely have the most discernable effects on increased water yield. However, the aggregated LULC changes would bring an increase in the proportion of consumed water, ending up in less available water after consumption. Nevertheless, local LUCC trends may cause different behaviors, for instance in the upper Chicú basin, where a recovery of Forests is expected.

We do note that our approach and study have some limitations. First, most DYNA-CLUE model applications have been in areas where there is, in general, greater availability of spatial data and information than in the Andes (Huggel et al., 2015). Similarly, the model assumes that the relationship between land use and drivers of change is linear and does not account explicitly for the influences of future policies or land use planning (Ren et al., 2019; Verburg and Overmars, 2009). Nevertheless, the CLUE series models have been assessed in different applications with several robust results (Pontius et al., 2008).

Our water provision service estimates also had some limitations. For example, our Goodness of Fit results between simulated and recorded flow for the Upper Bogota watershed were good, but our results for the Upper Chicú were only acceptable. This is primarily due to the influence of the estimated ET_o higher than expected (e.g. CAR, 2006) and that the data were interpolated from the only 3 stations available for the entire study area. We note that the hydrology of the Upper Bogota basin is particularly complex due to a highly heterogeneous landscape and topography as well as varying levels of aquifer recharge (Antonio-Fragala and Obregón-Neira, 2011). For example, there are four reservoirs within the study watersheds and there is also water transfer from adjacent basins; elements and interactions that are not accounted for in the InVEST model (Sharp et al., 2018).

Finally, our InVEST modelling approach was unable to estimate temporal variations in water yield particularly during the tropical dry and rainy season. Water yield may decrease in terms of annual balance, but it may be important to consider as decrease would occur mostly during the dry season months. Such findings would shed light on water scarcity in specific areas and LULCs or possible increased flood risk from urbanization of specific area and LULCs. In terms of our C stock and sequestration estimates, we only used study area specific biomass measurements for the Forest and Shrubland LULCs, while all other biomass values for the other LULCs in Table 2 were estimated from the literature. However, our integrated modelling approach did quantify the overall effects of influences of LUCC on ES and spatially identified specific areas of change. Nevertheless, our approach based on available models and data is straightforward and can be used by different stakeholders and successfully applied to other watershed in the region.

For example, recently proposed land use zoning changes in Bogota and other Latin America metropolitan areas include conversion of rural agricultural and forested lands to urban LULCs with higher real estate premiums, primarily at the cost of socio-economic equity and ecosystem services, particularly those related to water provision (e.g., Brookings University, 2019) Thus, approaches such as ours can be used by local governments to justify strategies to compensate for the loss of projected ES, specifically by: i) increasing the protection of ecosystems particularly relevant for water provision, e.g. paramos, ii) implement reforestation plans and protection of secondary forest growth, and iii) increase investment in improved land management practices by the agricultural and animal ranching sectors, to limit the current extensive use of the land.

5. Conclusions

This study modelled the cumulative and isolated effects of LUCC and two climate change scenarios on two disparate watersheds in the Colombian Andes. Given the rapid pace of socio-ecological change in these types of watersheds it is important to better understand the relative contributions of climate versus LUCC to water yield and carbon storage services. Overall, climate and LULC changes should result in an overall water yield reduction.

The cumulative effects of LULC and climate change indicate that urban development and land use policies for the Upper Bogota basin need to consider the potential adverse effects of urbanization on non-urban LULCs that provide a suite of ecosystem services. In particular, forest remain stable and have little effects on water yield, however urbanization of agricultural pastures can have substantial effects on water provision and carbon storage. Specific climate change adaptation policies generally focus on infrastructure and technologies related to water regulation systems for supply. However, in areas such as the Andes conservation of the remaining forests, shrublands and montane grasslands (paramos) is also key. Although land abandonment has reduced deforestation and transformed forests conversion patterns, further weakening of conservation policies could exacerbate the forests loss shown in our projections.

Towards these ends, temporally and spatially explicit scenarios and maps of where water yield is supplied and where carbon offsets are greatest can help direct land use decisions that maintain the supply of such services that are key to hydropower production and other consumptive uses and climate change mitigation measures. Such services and policies can be balanced with other co-benefits related to conservation or agriculture. This information can also be used to inform investments in restoration or management efforts benefitting downstream stakeholders such as hydropower companies. We hope that our methods, findings and recommendation from our research are relevant to policy makers, land managers and planners in promoting and advocating for the sustainable use of ecosystem services and as measures of climate change adaptation.

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Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.06.275.

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