Protocol for the Characterization of Carbon and Water Cycles in High-elevation Ecosystems of the Andes

The government of Colombia has taken a leadership role in facilitating research in high mountain ecosystems to provide a scientific base for understanding climate change and land use impacts on water and carbon cycles. With support from the World Bank and GEF, the Colombian Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) has undertaken a national pilot project on integrated adaptation to climate change (INAP). A key component of this project has been the development of a protocol for the characterization of carbon and water cycles in high-mountain ecosystems. The protocol is designed for use by government, university, and NGO partners interested in climate change impacts, with IDEAM leading the project and consolidating data and results. The present article provides an overview of the protocol design.

The protocol

High mountain ecosystems of the Andes, *páramo*, and Andean forests are potentially significant carbon sinks; together with glaciers they play an important role in regulating water flow. The Andes are unique in the number of large urban centers that are located above 2500 m, and these cities are dependent on mountain ecosystems for their water supplies. Tropical mountain regions of the Andean Cordillera have been identified as vulnerable to climate change (Büchler et al 2004). Anticipated impacts include higher temperatures and consequently greater evapotranspiration, an upward shift in the zero temperature gradient resulting in less snow relative to rainfall, glacial recession, and a vertical displacement of vegetation (Francou et al 2003, Vuille et al 2003, Hooghiemstra and van der Hammen 2004). Simultaneously, mountain headwater catchments are subject to anthropogenic impacts related to agricultural production, burning, wetland drainage, cattle grazing, and the clearing of forests and riparian vegetation (Hofstede 1995, Diaz and Paz 2002). The hydrologic implications of climate and land use change for the Andes potentially include a flashier runoff regime, less water storage capacity in wetlands, *páramo*, and glaciers, and less water availability in the dry season. Within Colombia the effects of climate change have already been documented; warming trends have been observed in minimum temperatures (Perez et al 1998), and the accelerated loss of ice cover of tropical glaciers is attributed to global temperature change (Ceballos 2006).

Management strategies for carbon and water require a scientific information base about the processes that affect the carbon and water cycles, their interactions, dynamics, variability, the practices that optimize storage, the effects of land use, vulnerability to perturbations, and potential implications for local communities. A protocol has been developed in Colombia as a tool to characterize carbon and water cycles in high-elevation Andean ecosystems and to facilitate comparative studies across the region. The protocol aims to establish a monitoring system to understand the impacts of climate change and land use on the capacity of these high mountain ecosystems to regulate water flow and to accumulate carbon.

The conceptual model

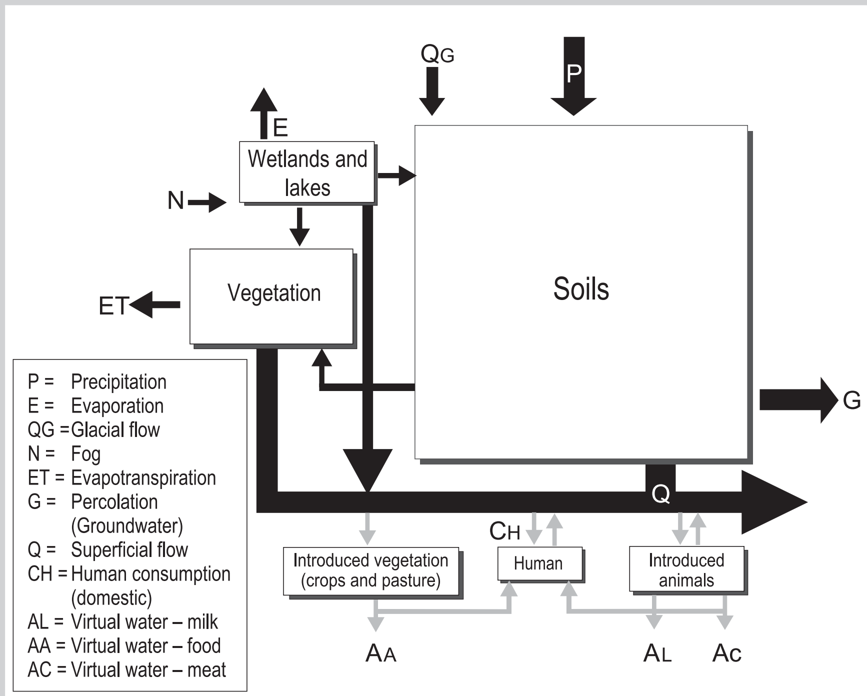
Evaluating the impacts of climate change and land use pressure on high-elevation ecosystems requires an understanding of the factors impacting the pools and flow paths of the carbon and water cycles. Carbon and water are stored in pools such as glaciers, wetlands, lakes, soils, and vegetation. Water and carbon pass from one pool to another through flow paths such as precipitation, decomposition, or evaporation. The protocol for the characterization of carbon and water cycles in high mountain ecosystems uses the concept of pools and flow paths to investigate the impacts of climate and land use on the various compartments and ultimately on carbon and water balances (CIAT 2006). Anthropogenic activities such as ploughing, burning, forest harvesting, and grazing modify the natural cycles through vegetation, introduced animals, and human consumption of water and biomass. Human influences are explicitly included within the protocol. The conceptual model is illustrated in Figure 1 for water in a *páramo* ecosystem.

Algorithm of the protocol

The protocol is organized in a series of blocks. Each block represents a flow of activities, analysis and decisions taken, and supporting documents to facilitate the application of the protocol. Norms and criteria, procedures, formats for data capture and instructions for the measurement of variables are associated with the blocks. The 7 blocks are:

1. Introduction to the protocol;
2. Selection of the sub-watershed and ecosystems to monitor;
3. Selection of research questions;
4. Collection of secondary data through a participatory process;
5. Design of the monitoring network;
6. Monitoring program;
7. Systematization and analysis of information.

FIGURE 1 Pools and flows of water in páramo with anthropogenic intervention.



Criteria are decision making guides such as criteria for the selection of sub-watersheds or prioritization of monitoring variables. Instruction sheets provide detailed explanations and procedures for installation, operation and maintenance of equipment, and standard methods for analysis. Formats are provided for the collection and compilation of field and/or laboratory data. Norms relate to World Meteorological Organization (WMO) or other international standards relative to data collection and/or analysis (eg EUROFLUX).

Selection of the sub-watersheds and ecosystems to monitor

The selection of the sub-watershed and ecosystems to monitor aims to account for the relative importance of the high-elevation ecosystems, their variability, and logistics for the implementation of monitoring. The criteria selected for Colombia are given in Table 1.

Research questions

Research questions are defined based on the characteristics of the selected micro-watersheds for monitoring, comparison between ecosystems, and consideration of climate change and land use impacts. Potential research questions include:

- Which pools within a non-intervened *páramo* ecosystem have the greatest capacity to hold water and regulate the water balance?
- How large are the carbon pools within a non-intervened high Andean forest ecosystem and what are their C accumulation rates?
- What are the impacts of human intervention on the ability of *páramo* ecosystems to hold water and regulate base flow?
- What are the rates of deglaciation; the principal factors driving deglaciation; and the impact on downstream *páramo* ecosystems?

Participatory baseline

Relevant geographic, biophysical, and socioeconomic secondary data are compiled and evaluated for data quality through a participatory process. Interest groups are identified and engaged through the formation of a Learning Alliance (Penning de Vris 2007). Indicators are validated at the local level so that secondary data collection focuses only on data relevant to carbon and water cycles in the specific high-mountain ecosystem under study. Geographical data of interest include base maps, land use and land cover maps, and existing imagery. Relevant biophysical data relate to climate, hydrology, water bodies and wetlands, water quality, glacial coverage and characteristics, vegetation inventories, and soil physical and chemical properties. Socioeconomic information of interest includes data on production systems, water use, and socioeconomic indicators such as education and land tenure. Responsibility for the collection of data is assigned to representatives of the interest groups, and existing data and metadata are compiled centrally and assessed for quality against international standards. Metadata variables to be assessed include the source of information, method of collection, sample size, scale, frequency of data collection, spatial coverage, and year(s) of data availability.

Design of the monitoring network

For each selected sub-watershed and the relevant research questions, the monitoring network is designed in accordance with criteria for the prioritization of variables and available resources (human and financial). For each pool and flow path of the water and carbon cycles specific to glaciers, *páramo*, and high-elevation Andean forests, a set of variables, required equipment, and methods of measurement are defined and prioritized. The ranking of variables is based on an index of: 1) contribution to or understanding of the pool or flow path, 2) complexity of measurement, and 3) cost of monitoring in terms of equipment and/or logistics. The monitoring network is then designed schematically considering

TABLE 1 Criteria for the selection of sub-watersheds and ecosystems to monitor.

Criteria for selection	High-mountain zones of interest >2750 m
Indispensable	Security Accessibility
Necessary	Local capacity Representative sub-watersheds Monitorability (area, drainage, homogeneity, etc)
Desirable	Comparable ecosystems Existing monitoring equipment Priority watersheds Use, shortages, or risks

existing equipment, priority variables for monitoring, and budget constraints. A series of "template" monitoring design drawings, criteria, and instruction sheets are provided as a guide for spatial and technical site selection.

The geographical/spatial monitoring design aims to provide high-resolution baseline imagery for inventory and temporal imagery to assess change in ecosystems and glaciers. The socioeconomic survey design identifies the basic socioeconomic information required for monitoring the carbon and water cycles and focuses on human intervention and adaptation. A draft questionnaire is provided which can be modified based on existing information and local validation. The principal sections of the survey include: family composition, land tenure, agricultural and agroforestry land use, livestock, farm management practices, on-farm forest cover, water sources, and water use.

Monitoring program

The monitoring program provides details for the installation of equipment and procedures for the collection of data corresponding to each selected variable. Key monitoring variables for water and carbon in *páramo*, high-elevation forest ecosystems,and glaciers are summarized in Table 2. For each biophysical variable, instruction sheets include information on equipment requirements, equipment installation (location and technical considerations), field measurements (site selection and technical considerations), maintenance and operation, results and analysis, equipment and laboratory costs, and norms.

Geographical/spatial monitoring is designed to provide baseline inventories of glaciers, water, vegetation, land use, and to monitor change over time (1, 5–10 year intervals). The socioeconomic component focuses on the implementation of the questionnaire, analysis of land management relative to the monitored ecosystems, and the measurement of water consumption.

All monitored variables are specifically linked to pools or flow paths.

Systematization

The systematization of data refers to the collection and transfer of information to a central database, and the analysis and synthesis of monitored variables to consolidate information at the project scale for the carbon and water cycles. Standard procedures for quality assurance and quality control are provided, including recommendations for station inspection, replicates, standard methods, and expected ranges. Instruction sheets are given for calculations for glacier mass and energy balances, water balance, estimation of the existing carbon pool, and C accumulation.

TABLE 2 Key monitoring variables for carbon and water cycles in *páramo*, high-elevation forests, and glaciers.

	Water cycle in *páramo* and high-elevation forest	Carbon cycle in *páramo* and high-elevation forest	Water cycle in glaciers
Inflows	Precipitation	Biomass production Fertilizer	Precipitation (rain/snow) Condensation
Pools	Wetland water volume Soil water content	Standing biomass C content of biomass C content in soils C accumulation rates (C^{14})	Aerial extent of the ice Ice volume (GPR) Glacial regression
Internal flows	Interception Infiltration Surface flow Subsurface flow Stable isotopes	Erosion Decomposition	Sublimation Fusion (climatic variables)
Outflows	Evaporation Transpiration (climatic variables) Stream discharge	Plant respiration Methane emission from wetlands Burning Harvesting	Stream discharge

The protocol is currently being validated at two sites in the Colombian Cordillera. Further information on the protocol is available in Spanish at: www.ideam.gov.co/inap.htm or contact Luz Dary Yepes luzdary@ideam.gov.co

REFERENCES

Büchler B, Bradley R, Messerli B, Reasoner M. 2004. Understanding climate change in mountains. *Mountain Research and Development* 24(2):176–177.
Ceballos JL, Euscátegui C, Ramírez J, Cañon M, Huggel C, Haeberli W, Machguth H. 2006. Fast shrinkage of tropical glaciers in Colombia. *Annals of Glaciology* 43(1):194–201.
CIAT [Centro Internacional de Agricultura Tropical]. 2006. Diseño del Protocolo para la Caracterización de los Ciclos de Carbono y Agua en Ecosistemas de Alta Montaña. Informe III. Modelo Conceptual, Algoritmo y Documentos de Soporte. Cali, Colombia: Centro Internacional de Agricultura Tropical.
Diaz EB, Paz LP. 2002. *Evaluación del régimen de humedal del suelo bajo diferentes usos, en los páramos Las Animas y Piedra de León, Departamento del Cauca* [MSc thesis]. Popayán, Colombia: Fundación Universitaria de Popayán.
Francou B, Vuille M, Wagnon P, Mendoza J, Sicart JE. 2003. Tropical climate change recorded by a glacier in the central Andes during the last decades of the twentieth century: Chacaltaya, Bolivia, 16°S. *Journal of Geophysical Research* 108(D5):4154. doi:10.1029/2002JD002959.
Hofstede R. 1995. *Effects of Burning and Grazing on a Colombian Páramo Ecosystem* [PhD dissertation]. Amsterdam, The Netherlands: University of Amsterdam.
Hooghiemstra H, van der Hammen T. 2004. Quaternary ice-age dynamics in the Colombian Andes: Developing an understanding of our legacy. *Philosophical Transactions of the Royal Society of London, Biological Sciences* 359:173–181.
Penning de Vris FWT. 2007. Learning alliances for the broad implementation of an integrated approach to multiple sources, multiple uses and multiple users of water. *Water Resources Management* 21:79–95.
Perez CA, Poveda G, Mesa OJ, Carvajal FL, Ochoc A. 1998. Evidencias de cambio climático en Colombia: Tendencias y cambios de fase y amplitud de los ciclos anual y semianual. *In:* Cadier E, Gómez G, Galarraga R, Fernández-Jáuregui C, editors. *Consecuencias climáticas e hidrológicas del evento El Niño a escala regional y local. Incidencia en América del Sur.* Montevideo, Uruguay: United Nations Educational, Scientific and Cultural Organization. Available online at http://www.unesco.org.uy/phi/libros/enso/; accessed on 20 September 2007.
Vuille M, Bradley R, Werner M, Keimig F. 2003. 20th century climate change in the tropical Andes: Observations and model results. *Climate Change* 59:75–79.

Sandra Brown
Institute for Resources, Environment and Sustainability, University of British Columbia, Rm 417 AERL Building, 2202 Main Mall, Vancouver BC, Canada V6T 1Z4.
sjbrown@interchange.ubc.ca

Clara Roa, Cecilia Roa
International Center for Tropical Agriculture (CIAT), Km 17 Recta Cali-Palmira, Palmira, Colombia.
c.roa@cgiar.org; m.roa@cgiar.org

Luz Dary Yepes
Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), Carrera 10 No. 20–30, Bogotá DC, Colombia.
luzdary@ideam.gov.co

doi:10.1659/mrd.0953

The Sierra Nevada Lobby Day: Putting the "Range of Light" on the Map

As many mountain scholars have already emphasized, advocacy of the specificity of mountain environments and communities at the international, national and regional levels is a decisive step towards sustainable mountain development. It is an essential task to stress the importance of mountains in the political arena. This short report gives an account of an original initiative: The Sierra Nevada Lobby Day.

This event, carried out on an annual basis, was held on 5 June 2007 and sponsored by The Sierra Fund and the Sierra Nevada Alliance. The former organization is a non-profit community foundation aiming "to support environmental conservation in the Sierra Nevada region." The latter is an alliance of conservation groups, with a mission "to protect and restore the natural resources of the Sierra Nevada for future generations while promoting sustainable communities." The event took place where decisions concerning the Sierra Nevada are made: in the California State Capitol in Sacramento (USA). The concept of the Lobby Day is to welcome any citizen concerned about the fate of the "Range of Light," the name bestowed by the famous environmentalist John Muir, which became the common nickname for the Sierra. There were about thirty participants at the 2007 meeting, mainly members of organizations already active in the Sierra.

It is worth noting how this event was organized. First, a plenary session offered the participants a general overview of the issues in the Sierra and the main target objectives for the year. Second, a specialist in lobbying provided insights into this specific activity and tips for carrying it out. Third, small groups of from 2 to 4 newly proclaimed lobbyists were organized. Fourth, the groups went from door to door of the offices of the Senators and Assemblymen in the State Capitol (the elected representatives in the two Chambers of the California parliament), calling on them to plead the cause of the Sierra. Finally, the day ended with a debriefing for the participants regarding an evaluation of how the message transmitted was received.

The issue at stake for 2007 was the approval of the budget of the Sierra Nevada Conservancy. This California state agency, created in 2004, "initiates, encourages, and supports efforts that improve the environmental, economic, and social well-being of the Sierra Nevada Region, its communities and the citizens of California." It covers an area of 25 million acres, all or part of 22 counties. The organization needed this money for its operations and to launch a grant support program (US$ 17.5 million of a global budget of US$ 21.6 million). The "day-lobbyists" gave a summary of projects oriented towards the