A Preliminary Investigation of the Soils and Geomorphology of a Portion of the Madre de Dios Region, Peru

Daria Nikitina, Liudmila Remizova, and Russell L. Losco

Development of soil profiles in the southwestern Amazon basin is closely related to geomorphology, hydrology, and age of fluvial landforms. Three fluvial terraces were identified in the Madre de Dios watershed at approximately 12°34′07″S and 70°05′57″W. The oldest and the highest terrace formed in the late Miocene-Pleistocene probably in response to tectonic uplift. The soil developed at this elevated, dissected, and poorly drained alluvial surface (terra firme) exhibited strong weathering and was preliminarily classified as an Acroperox. The accumulation of the second terrace is probably related to an unusually wet period with an enhanced rate of weathering in the Andes and Altiplano around 29 to 25 ka. The soil developed at the second terrace is likely a Perox. The youngest terrace or high floodplain began to form during the Younger Dryas and continued until about 3.7 ka BP. The soils capturing its surface are developing on a sandy loam, show well-preserved sedimentary structure, and are likely Alfisols or Ultisols. The latest stage of alluvium aggradation lasted until about 870 BP and resulted in formation of the modern floodplain. Despite lateral erosion and active mass wasting, during the wet season the floodplain is 20 to 30 m wide on both sides of the channel. The soil of the floodplain (Entisols) is in its early stage of development, showing evidence of recent deposition. It is subject to frequent surface flooding and constant soil saturation by groundwater. The exceptional biodiversity of this remote region is likely related to fluvial dynamic, soil development, and diverse landforms that appear in response to tectonic activity or climate change. Better understanding of the landscape development through time and structure of the rain forest is necessary for future assessment of the impact of climate change on tropical ecosystems.

In August 2010 a group of students and faculty from Moscow State University (MSU), Russia led by Dr. Daria Nikitina, a geomorphologist from West Chester University, USA and an alumnus of MSU traveled to southern Peru for a 20-d educational expedition. During the trip the group visited the Centro de Investigacion y Capacitacion Rio de los Amigos (CICRA), the scientific field station located in the department of Madre de Dios. The station was established in 2000 and operates under the management of the Amazon Conservation Association (ACA), its mission to serve as a research and educational center in one of the most remote parts of the Amazon basin. The basin itself is the world's largest fluvial sedimentary basin and currently supports the largest continuous area of tropical lowland forest (Räsänen et al., 1992). The Department of Madre de Dios is located in the southwestern portion of the basin which has been identified as one of the "Global 200" biodiversity hotspots (Olson and Dinerstein, 2002) and hence is a focus of national and international conservation efforts. However, this remote, sparsely populated region is little explored because of its vast area and limited access. The basic information on the region's geology, soils, hydrology, and climate remains very sketchy. The lack of stratigraphic information, numerical age dates, and knowledge about origin and characteristics of surficial sediment prevents resolution of its geologic history and understanding contemporary landscape development. Poor knowledge of regional soils presents challenges for assessment of their fertility and comparison with other sites in Amazonia or the Neotropics. The most current soil classification for the Department of Madre de Dios is based on the study of one site in the vicinity of Puerto Maldonado and Laberinto about 100 km east of the CICRA station (Osher and Buol, 1998). The basic information about the area's ever-changing fluvial environment and soil descriptions may be essential for further geologic investigations and developing best conservation strategies.

While at CICRA, the group conducted a 5-d field investigation of fluvial landforms, sediments, and soil horizons in the vicinity of the station between the main channel of the Madre de Dios and its tributary, the Los Amigos River (Fig. 1). The purpose of this pilot field project was to collect basic geomorphologic information and soil data that may become useful for future scientific research. This investigation was conducted in the context of an educational expedition actively engaging students to contribute to scientific knowledge.

Daria Nikitina, West Chester University, Dep. of Geology and Astronomy, 750 S. Church Street, West Chester, PA 19383 (dnikitina@wcupa.edu); Liudmila Remizova, Moscow State University, Dep. of Geography, Moscow, 119234, Russia; Russell L. Losco, Lanchester Soil Consultants, Inc., 311 East Avondale Road, West Grove, PA 19390.
doi:
Published in Soil Surv. Horiz. 52(2):40–47 (2011).

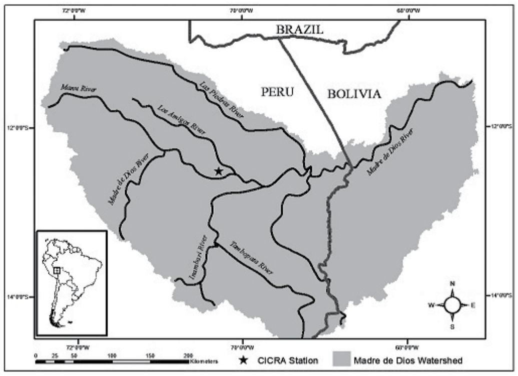

Fig. 1. Location of the Madre de Dios watershed in Peru and Bolivia. The study area is located in the vicinity of CICRA station.

Study Area

The study area was located in the lowland portion of the Madre de Dios River watershed close to the confluence of the mainstream with the Los Amigos River. The Madre de Dios River drains part of the Sub-Andean Fold and Thrust Belt along the Eastern Cordillera (Dumont et al., 1991). The watershed covers approximately 90,000 km^2 (Goulding et al., 2003). The lowland portion of the main watershed and the Los Amigos watershed are part of the Amazon foreland basin that runs along the eastern foothills of the Andes. The modern drainage system was developed on top of alluvial, lacustrine, and tidal deposits of the Madre de Dios formation of Miocene to late Pliocene age (Campbell et al., 2001; Antoine et al., 2003; Hovikoski et al., 2005). The formation is represented by complex variations of facies and extends through the central and southern Peruvian Amazon Basin. A detailed stratigraphy and geochronology based on two ages of ash layers found at the base and uppermost portion of the formation was presented by Campbell et al. (2001) for the location ~250 km north and ~60 km northeast of the study area. The authors subdivided the Madre de Dios formation into three units (Fig. 2). It is possible that basal unit A, which was described by the authors as clay–pebble or clay–ball conglomerate, is exposed at the channel of the Madre de Dios River at the CICRA station (Fig. 3), indicating that the modern river is downcutting all the way to the base of the formation. The top unit C forms the terra firme, the highest geomorphologic surface in lowland Amazonia (Sombroek, 1966; Campbell et al., 2001). Terra firme is the widespread dissected alluvial surface that covers the main part of the Peruvian Amazon foreland basin (Räsänen et al., 1992). While the origin of the top alluvium is somewhat controversial, the sedimentation was controlled by Miocene-Pleistocene tectonic deformation of the Andes and their foreland and climatic changes accompanied by the development of a paleodrainage network (Uba et al., 2007). The tectonic activity in the Peruvian foreland basin is related to the geometry of the subducted Nazca plate and its segmentation (Jordan et al., 1983). The Madre de Dios area is located above a gently dipping (5–10°) slab segment and is characterized by eastward migrating tectonism related to crustal shortening. It has been suggested that morphologic evidence of recent deformations within the basin is the occurrence of asymmetrical terraces on the northeastern bank of the Madre de Dios (Räsänen et al., 1992), indicating that the river system migrates laterally to the southwest becoming parallel to the Sub-Andean thrust zone (Räsänen et al., 1990).

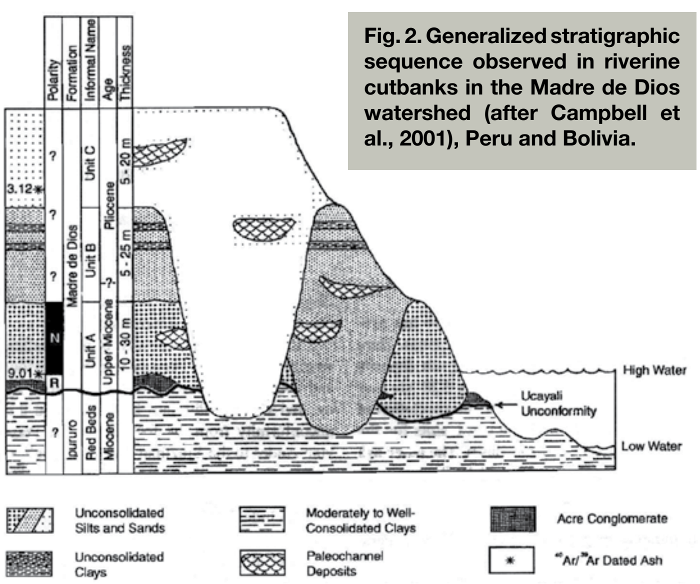

Fig. 2. Generalized stratigraphic sequence observed in riverine cutbanks in the Madre de Dios watershed (after Campbell et al., 2001), Peru and Bolivia.

The CICRA station is located on the Madre de Dios River approximately 6 km upstream from its confluence with the Los Amigos River (Fig. 1). The seasonal variation of water level in the river exceeds 8 m (Hamilton et al., 2007; Pitman, 2008). Even though the absolute elevation of the

Fig. 3. Conglomerate debris observed at the Madre de Dios channel at low water level.

river channel has not been surveyed, the elevation at the base of the cliff is reported to be 230 m above sea level (asl) (Pitman, 2008). The station itself was built on terra firme at the elevation 268 to 270 m asl.

The modern landscape of the study area is predominantly fluvial with wide meander scroll belts next to main channels, extensive floodplains, numerous oxbow lakes, and terraces (Fig. 4). The relief of terra firme, the original alluvium aggradational surface, also reveals abandoned channels, indicating that the material was deposited by the laterally migrating meandering channels. Sediments of floodplain and terraces are exposed in modern cutbanks (Fig. 5) and consist of three facies associations: (i) channel, (ii) point bar, and (iii) floodplain (Rigsby et al., 2009). The terrace stratigraphy exposed along the river banks shows stacked up sequences of fining upward fluvial cycles, indicating multiple stages of river incision likely associated with cyclic glaciation of the Andes during the Pleistocene (Räsänen et al., 1990). The soils developed on various fluvial deposits and geomorphologic surfaces of different age are not similar. The previous surveys of soil horizons indicated that predominant soils of the terra firme are well-drained, red or yellow Ultisols and Oxisols; however the latter has limited occurrence (Kalliola et al., 1993). There are also two different types of soils reported to form on the floodplains: the young poorly stratified Entisols and wet poorly drained Inceptisols, which are sufficiently older and typically occur in palm swamps. However, due to the complexity of floodplain hydrology, distribution of floodplain landforms, and the variety of floodplain ecosystems mapped and described in the Madre de Dios and Los Amigos watersheds (Hamilton et al., 2007), this classification is very basic.

The study area has a humid tropical climate with annual rainfall varying from 1200 to 3300 mm (Osher and Buol, 1998). Rainfall is seasonal with the lowest precipitation from June to September and the wet season during January and February. Flooding events on all the rivers in the region are poorly recorded (Pitman, 2008). The river stage data available for the Madre de Dios River is limited to the time period from 2001 to present and referenced to arbitrary zero datum; the absolute elevation of the gauge has not been surveyed (Pitman, 2008). The stage record documents the average annual range of 8 m and above and shows the same seasonal pattern as the precipitation data (Hamilton et al., 2007). However, rapid short-term fluctuations of 2 to 3 m/d may occur at any time of year, indicating a rapid response of the river to individual storms with the watershed (Barthem et al., 2003). Terrace surfaces are located above the reach of present-day river flooding but may be quite wet from accumulation of rainfall and local runoff (Hamilton et al., 2007).

Materials and Methods

Landsat 2000 satellite imagery and high resolution aerial photos were used to examine and classify fluvial landscapes in the vicinity of the CICRA station. Floodplains along the Madre de Dios and Los Amigos Rivers were accessed by foot. Since the field work was conducted in August, during the dry season, the lower water level allowed a detailed description of rocks and sediments exposed in the channel of Madre de Dios to be conducted. Photographs documenting rock types, sedimentary structures, and their exposure along the main channel were taken. A 2-km-long transect from the main channels of Madre de Dios to Los Amigos was set up. Coordinates and elevation at points where slope elevation changed were recorded using global positioning system (GPS) receivers and inputted into Google Earth. A topographic profile across the interfluves was developed using elevations recorded in the field and distances measured from Google Earth imagery.

Fig. 4. Google Earth image of the study area showing transect across interfluve between Madre de Dios and Los Amigos rivers.

Fig. 5. Outcrops of the Madre de Dios floodplain deposits exposed in the vicinity of CICRA: (a) MD1 site and (b) MD2 site.

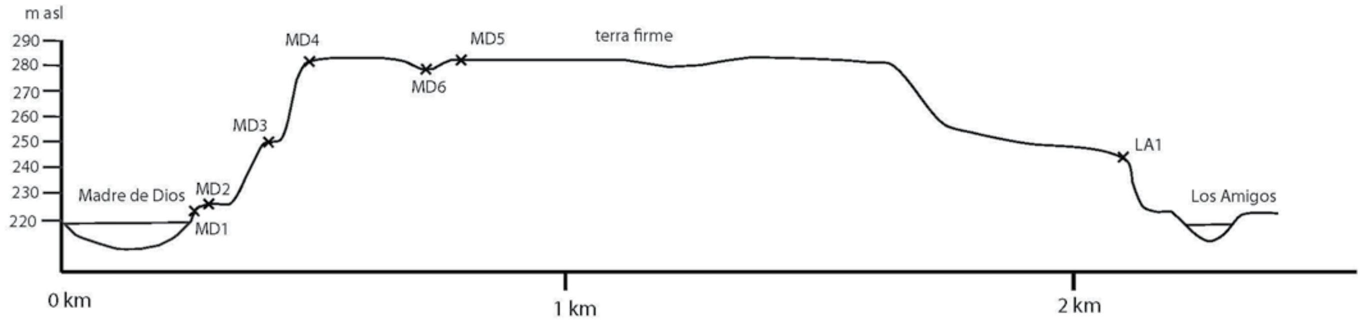

Fig. 6. Topographic profile showing elevation of identified terraces and soil description sites in the Madre de Dios floodplain of Peru and Bolivia.

Seven sites for stratigraphic investigations and sample collection were selected along the transect. Soil profiles were described and photographed in the field at the selected sites. The boundaries between horizons were identified visually based on changes in color, texture, and organic content. Sediment samples were taken from selected horizons and transported to the laboratory for further analysis. Grain-size analysis was performed at the sedimentology lab at Moscow State University using an Analysette 3 PRO sieve shaker and Analysette 22 laser diffraction grain-size analyzer (Fritsch GmbH, Germany).

Results

Fluvial Terraces

The topographic profile was developed between meanders across the interfluves of two drainage systems (Fig. 6). The profile connects meander cutting banks of both streams (Fig. 4). Despite active erosion and documented mass wasting, 20- to 30-m-wide floodplains are developed along both channels. Low and high floodplain surfaces separated by 1.8- to 2-m steps were documented along the Madre de Dios channel. A distinct fluvial terrace that rises above the floodplain to the elevation of 243 to 249 m asl was present in both basins. Terrace tread along the Madre de Dios side was relatively narrow, reaching only ~10 m at the southern end of the transect but well defined in the landscape (Fig. 7). On the Los Amigos side, the same terrace reached a width of ~400 m. Its tread gently sloped toward the river channel, while the riser was covered by a mantle of colluvium. The terrace was wide and well preserved on both sides of the Los Amigos valley (as it can be seen on high resolution aerial photos or Google Earth imagery), but only narrow segments of it may be identified elsewhere within the Madre de Dios watershed. In the field, only the northern bank of the Madre de Dios was investigated, where just fragments of this terrace were preserved because the bank was subject to active mass wasting during the wet season (Fig. 7).

The highest terrace (terra firme) was a relatively flat dissected interfluve with remnants of fluvial landforms such as oxbows and a drainage network developed on old alluvium. The surface was at the elevation of 280 m asl.

Soils

The soils were examined along a transect beginning on the floodplain of the Madre de Dios River stretching across the interfluve down to the Los Amigos watershed (Fig. 6). Six sites within the Madre de Dios valley and on the interfluve were investigated and labeled MD1-MD6. Only one site, LA1 was investigated on the fluvial terrace of the Los Amigos River. The soils were described in an anecdotal fashion but were also well photographed, allowing some correlation to USDA's *Keys to Soil Taxonomy* (Soil Survey Staff, 2006).

Pedon MD1 was located at the lowest elevation, approximately 221 m asl, on the floodplain of the Madre de Dios River (Fig. 6). The soils encountered exhibited evidence of recent deposition in that they were stratified and of varying parent materials; however, soil development was evident (Fig. 8a). A weak epipedon was found at the surface, but most of the horizonation appeared to be relict from the depositional environment. There was some color formation within the profile, indicating that soil development is occurring but is in its early stages. Soils were of a sandy loam texture throughout the profile, although some silt and clay accumulations were noted within the lowest horizons at the depth of 1.2 to 1.8 m, although these may be rip-up clasts. These soils are likely classified as Entisols, most likely Arents.

Pedon MD2 was located on the same terrace as MD1 but 2 m higher and 20 m further away from the river bank (Fig. 6). More profound soil development was found here, with a definite 10-cm-thick epipedon as well as an apparent argillic horizon beginning at a depth of 33 cm. Distinct redoximorphic concentrations and depletions of iron were evident

Fig. 7. Erosive bank of the Madre de Dios River near the CICRA station in Peru. Photo illustrates evidence of active mass wasting and a narrow segment of a fluvial terrace.

Fig. 8. Soil profiles described at the following sites: (a) MD1, (b) MD2, (c) MD3, (d) MD4, (e) MD5, (f,g) MD6 in the Madre de Dios watershed in Peru and Bolivia.

at a depth of 74 cm and became prominent and coarse at 1.15 m (Fig. 8b). Strong structure was evident throughout. Textures were sandy loams from the surface down to 1.15 m, where a transition to a silty clay loam texture was noted. This was followed by another sandy loam horizon from 1.67 to 1.75 m depth, then a transition into a silt loam at 1.75 m underlain by a firm silty clay loam at 1.93 m. These soils were more developed, as evidenced by the heavier textured lower horizons, and may be older. These soils are most likely Alfisols or Ultisols.

Pedon MD3 was located on the next higher terrace at an elevation of 250 m asl. Increased rubification was immediately evident in this soil, with matrix hues in the 10R range (Fig. 8c). The beginning of a weakly developed, 3-cm-thick epipedon was noted. The soil was less horizonated and contained concretions and soft masses of iron. Surprisingly, the textures of these soils were loamy sands with sand fractions in the 78 to 80% range. This soil is likely an Oxisol, possibly a Perox.

The following three sites, MD4 through MD6 were located on terra firme, but absolute elevation of each site varied. MD4 was located at an elevation of 280 m asl. Increased leaching of the profile was evident. The bright reds of MD3 were no longer evident and colors were in the 10YR to 2.5Y hue range (Fig. 8d). Some faint redoximorphic depletions of iron were visible. The leached colors probably correlate to a lower base saturation level. The textures of the soils were loamy sands with sand fractions ranging from 58 to 78%. This soil is most likely an Oxisol, possibly an Acroperox or a Eutroperox; however, lab analysis would be needed to confirm such a classification.

Pedon MD5 was located at an elevation of 284 m asl. This site was only explored to a depth of 50 cm due to site constraints; however, the colors were similar to MD4, suggesting similar levels of weathering (Fig. 8e). These soils were not sampled. This soil is also most likely an Oxisol, possibly an Acroperox or a Eutroperox, but further investigation would be needed to confirm this classification.

Pedon MD6 was located at an elevation of 277 m asl. This soil profile exhibits strong weathering, with possible inclusions of visible kaolinite in the profile. Redoximorphic depletions and concentrations were common, coarse, and prominent, suggesting somewhat poor drainage. This is consistent with the findings of Osher and Buol (1998), who found the best drainage adjacent to the river and progressively less well-drained soils moving laterally away from the river and upward on the landscape. This profile was also distinctly different in that it exhibited a thick (14 cm) surface horizon dominated by rounded cobbles of mixed lithology (Fig. 8f,g). These cobbles composed 50% or more of the horizon by volume, were rounded, and apparently fluvial in nature. The textures of these soils were finer, exhibiting sandy loam textures throughout to a depth of 88 cm before transitioning into a sandy clay loam from 88 cm to 1.26 m in depth. This increase in the fine soil fraction suggests more soil development. This soil is also most likely an Oxisol, possibly an Acroperox or a Eutroperox, but again, lab analysis would be needed to confirm this classification.

The soil encountered on the Los Amigos side of the transect, LA1, was located on the terrace at an elevation of 243 m asl. This terrace (Fig. 6) correlated to the Madre de Dios terrace where soil profile MD-3 was investigated. LA1 exhibited soil development with the beginnings of an epipedon that was only 37 cm thick and high in organic matter but with little translocation of clays. The soil was sandy, exhibiting loamy sand textures where sampled, and the horizonation appeared to be strongly related to the depositional environment rather than soil formation (Fig. 9). There was some color formation within the profile, indicating that soil development is occurring but is in its early stages. These soils are likely to be Entisols, specifically Arents, but may be Inceptisols.

Fig. 9. Soil profile described at the fluvial terrace of the Los Amigos River, Peru.

Discussion

Three distinct flat surfaces including floodplain and terra firme identified in the study area correspond well to three laterally extensive Quaternary terraces documented and dated in the Madre de Dios basin by Rigsby et al. (2009) (Fig. 10). The oldest and highest terrace (T3) formed on the late Miocene-Pleistocene fluvial strata of terra firme. The age of the fluvial strata underlying the terrace surface is not well constrained but is most likely more than 48 ka BP (Rigsby et al., 2009; Antoine et al., 2003). The age of the fluvial sediments estimated at the base of the middle terrace (T2) discontinuously present through the river valley dates back to 29 to 25 ka BP (Rigsby et al., 2009). Plant fossils retrieved from the lowest and the youngest terrace (T1) were from 11 ka to 3780±50 cal yr BP. The age estimates of terraced fluvial sequences suggest that the terraces were formed by three distinct aggradational periods followed by episodes of downcutting. The first aggradational period that resulted in formation of the terra firme occurred likely in response to a phase of enhanced uplift during the late Miocene-Pliocene (Steffen et al., 2009; Schildgen et al., 2007; Campbell et al., 2006) and ended before 48 ka (Antoine et al., 2003). When the incision of Madre de Dios in terra firme began is unknown, but the first downcutting resulting in the formation of the highest terrace was finished by 29 ka (Rigsby et al., 2009). The deposition of the T2 sedimentary sequence began 29,780 ±100 cal yr BP and probably lasted until 25,040±130 cal yr BP. The downcutting on T2 occurred sometime between 25 ka and before ~12 ka BP (Fig. 10). Aggradation of the youngest terrace started ~11,970 cal yr BP and lasted until 3780 ± 50 BP, after which the river began the new phase of aggradation that lasted until 870 ± 50 BP (Rigsby et al., 2009).

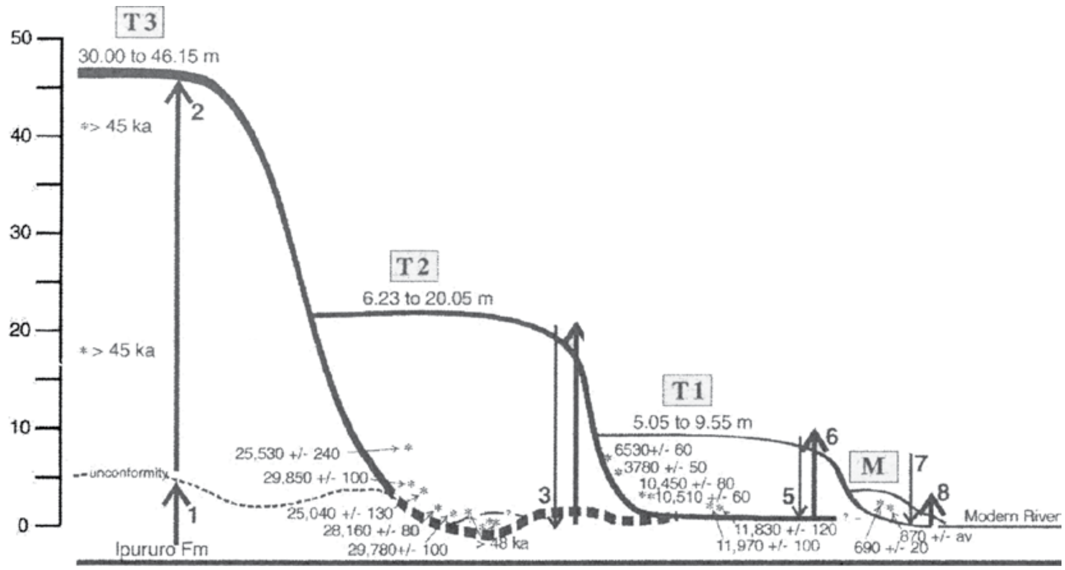

Fig. 10. Elevation model of the Madre de Dios fluvial terraces showing typical heights for each terrace, stages of aggradation, and episodes of downcutting and radiocarbon dates in calibrated years BP (after Rigsby et al., 2009) in Peru and Bolivia.

Terraces of the Madre de Dios basin may be compared to stages of sediment accumulation and erosion that formed cut-and-fill terrace tracts in the Pisco valley in central Peru. Luminescence dating of Pisco's fluvial deposits revealed three stages of sediment aggradations resulting in formation of the highest terrace sequences between 54 and 38 ka, the lower terraces between 27 and 16 ka, and the lowermost terrace sequence between 11 and 4 ka (Steffen et al., 2009). Time intervals of sediment aggradation of the two highest terraces in the central Andes were contemporaneous with periods of intense precipitation beginning 54.8 ka ago and 26 to 14.9 ka ago (Steffen et al., 2009), the timing of enhanced easterly winds and unusually wet period on the Altiplano, resulting in formation of paloelakes (Baker et al., 2001). Sediment core records from Lake Titicaca, neighboring with the Madre de Dios headwaters, show that the climate during the entire last glacial (60–20 ka) period was cold and wet (Fritz et al., 2007) and as a result may have produced rapid rates of erosion of highland tributaries, increased discharge, and likely, sediment aggradation in the lower reaches. The transition period between pluvial intervals was predominantly dry (Fritz et al., 2004). High discharges and increased stream capacity associated with intense precipitation would explain accumulation of gravel clasts (up to 12 cm in diameter) in channel lags documented at MD-6 (Fig. 8f). Phases of erosion may have started during the last stages of pluvial periods when sediment discharge decreased, but stream capacity stayed the same, triggering sediment transport leading to the erosion of previously deposited material (Steffen et al., 2009; Tucker and Slingerland, 1997). Stream incision may have continued or slowed during dry periods stabilizing the channel at the lower level. However, establishing the relationship between the incision of the Madre de Dios into terra firme (the highest terrace) and downcutting of the lower terrace with paleoclimate requires more supporting data. Aggradation of the lowest terrace in the Madre de Dios and Pisco valleys began during the Younger Dryas, which was a very dry period on the Altiplano and in the lowlands (Baker et al., 2001; Mayle et al., 2007). As for now, there is no evidence that links climate variations and late Holocene downcutting of the lowest terrace (floodplain) of Madre de Dios. Therefore, factors controlling the river incision and aggradation are still not well understood.

Soils profiles described in this study were formed on fluvial terraces of different ages. Osher and Buol (1998) concluded that all of the upland soils in the vicinity of Puerto Maldonado, which is about 100 km down the stream, were Ultisols. The evidence of strong weathering in the soils encountered on terra firme and the second terrace suggest the presence of some soils that are potential Oxisols; however, further research will be needed to confirm that conclusion. The fairly recent soils encountered at MD1, MD2, and LA1 suggest recent deposition and soils at the early stages of development. The soils encountered at MD3 with the high degree of oxidation strongly suggest that this is an Oxisol or on its way to becoming one. The strongly leached appearance of the soils at MD4, MD5, and MD6 similarly suggest that they may be Oxisols rather than Ultisols.

The further comparison of the soils at MD3 and LA1 is of interest. They appear to be at similar stages of development, which would be expected at similar elevations and landscape positions. They therefore appear to be contemporary, yet show significant differences, such as the thick organic-rich epipedon at LA1 that is lacking at MD3. Osher and Buol (1998) suggested that the composition of the soils drive the formation of the channels with sandy soils occupying one bank and finer-textured soils occupying the opposite bank. Osher and Buol, however, did not describe any fluvial terraces within their study area. A dichotomy in the soil composition could explain the lack of certain terraces; that is to say that if the soils on the Los Amigos side contained a higher sand content and were therefore less cohesive, then they could be expected to experience higher rates of erosion. However, such a dichotomy was not found. Instead, similar textured soils were found on MD-3 and LA-1. Some other mechanism must explain this process. It is hoped that future research could shed some light on this.

Conclusions

The results of this pilot study indicate that soils are closely related to different features of the fluvial landscape. Detailed analysis of fluvial terraces and the soils that they contain may explain the past cycles of sediment accumulation and erosion. Some of these cycles are related to climate change, but others remain unknown. Future investigations over broader areas are necessary to develop a landscape evolution model of the Peruvian Amazon Basin and its relationship to the Andean tectonics and global climate change. In particular, more dating is required to better constrain the timing of aggradation and downcutting. Reconstruction of fluvial landscape development and paleoclimate history are important components in understanding the impact of current climate changes on global systems. The Madre de Dios and Los Amigos basins support one of the most diverse ecosystems in the world, and yet very little is known about the relationship between geomorphology, soils, hydrology of the floodplain, and structure of the rain forest. A multidisciplinary study designed to link sedimentological characteristics of substrate, processes of soil development, and the biological communities that they support could be of significant value in understanding tropical ecosystems. The CICRA station would be a perfect site to continue systematic mapping and investigation of the soils and geomorphology of an extensive area because it is an established research facility. Also, it was formerly a gold mining camp, and much of the surrounding forest is second growth, so the site could be used as a model of anthropogenic influence on the soils of a tropical rain forest area over time. Finally, the existence of the fluvial terraces provides a unique opportunity to investigate soil development over time on discrete surfaces under differing conditions.

Acknowledgments

We wish to thank ACEER (Amazon Center for Environmental Education and Research) for organizing the trip, putting together a great itinerary, and supporting Dr. Daria Nikitina; Richard Amable for guiding us through the jungle; Dr. Nigel Pitman for sharing his knowledge about the study area; ACA and CICRA staff for their hospitality and data sharing; Andrew Kaufman and Pedro Owsik, West Chester University students, for helping in preparation of this manuscript; and the group of Moscow State University students and faculty for their patience and travel companionship.

References

Antoine, P.-O., P. Baby, S. Brusset, W. Hermoza, and M. Roddaz. 2003. Informe de campo: Geologia de la Concecion Los Amigos, Mision de Reconocimiento, Universite Paul-Sabatier, Tolouse France.

Baker, P.A., G. Seltzer, S. Fritz, R. Dunbar, M. Grove, S. Cross, P. Tapia, H. Rowe, and J. Broda. 2001. The history of South American tropical precipitation for the past 25,000 years. Science 291:640–643. doi:10.1126/science.291.5504.640

Barthem, R., M. Goulding, B. Forsberg, C. Cañas, and H. Ortega. 2003. Aquatic ecology of the Rio Madre de Dios: Scientific bases for Andes-Amazon Headwaters conservation. Amazon Conservation Association, Lima.

Campbell, K., M. Heizler, C.D. Frailey, L. Romero-Pittman, and D.R. Prothero. 2001. Upper Cenozoic chronostratigraphy of the southwestern of Amazon Basin. Geology 29(7):595–598. doi:10.1130/0091-7613(2001)029<0595:UCCOTS>2.0.CO;2

Campbell, K., C.D. Frailey, and L. Romero-Pittman. 2006. The Pan-Amazonian Ucayali Peneplain, late Neogene sedimentation in Amazonia, and the birth of the modern Amazon River system. Palaeogeogr. Palaeoclimatol. Palaeoecol. 239:166–219. doi:10.1016/j.palaeo.2006.01.020

Dumont, J.F., E. Deza, and F. Garcia. 1991. Morphostructural provinces and neotectonics in the Amazonian lowlands of Peru. J. South Am. Earth Sci. 4:373–381. doi:10.1016/0895-9811(91)90008-9

Fritz, S.C., P. Baker, T. Lowenstein, G. Seltzer, C. Rigsby, G. Dwyer, P. Tapia, K. Arnold, T. Ku, and S. Luo. 2004. Hydrologic variation during the last 170,000 years in the southern hemisphere tropics of South America. Quat. Res. 61:95–104. doi:10.1016/j.yqres.2003.08.007

Fritz, S.C., P. Baker, G. Seltzer, A. Ballantyne, P. Tapia, H. Cheng, and L. Edwards. 2007. Quaternary glaciations and hydrologic variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. Quat. Res. 68:410–420. doi:10.1016/j.yqres.2007.07.008

Goulding M., C. Cañas, R. Barthem, B. Forsberg, and H. Ortega. 2003. Amazon headwaters: Rivers, wildlife, and conservation in southern Peru. Amazon Conservation Association, Lima.

Hamilton, S.K., J. Kellndorfer, B. Lehner, and M. Tobler. 2007. Remote sensing of floodplain geomorphology as a surrogate for biodiversity in a tropical river system (Madre de Dios, Peru). Geomorphology 89:23–38. doi:10.1016/j.geomorph.2006.07.024

Hovikoski, J., M. Räsänen, M. Gingras, M. Roddaz, S. Brusset, W. Hermoza, and L. Romero-Pittman. 2005. Miocene semidiurnal tidal rhythmites in Madre de Dios, Peru. Geology 33(3):177–180. doi:10.1130/G21102.1

Jordan, T.E., B.L. Isacks, R.A Allmendinger, J.A. Brewer, V.A. Ramos and C.J. Ando. 1983. Andean tectonics related to geometry of subducted Nazca plate. GSA Bull. 94(3):341–361. doi:10.1130/0016-7606(1983)94<341:ATRTGO>2.0.CO;2

Kalliola, R., A. Linna, M. Puhakka, J. Salo, and M. Räsänen. 1993. Mineral nutrients in fluvial sediments from the Peruvian Amazon. Catena 20:333–349. doi:10.1016/0341-8162(93)90009-E

Mayle, F.E., R. Langstroth, R. Fisher, and P. Meir. 2007. Long-term forest–savannah dynamics in the Bolivian Amazon: Implications for conservation. Philos. Trans. R. Soc. London B 362:291–307 doi:10.1098/rstb.2006.1987

Olson, D.M., and E. Dinerstein. 2002. The Global 200: Priority ecoregions for global conservation. Ann. Mo. Bot. Gard. 89(2):199–224. doi:10.2307/3298564

Osher, L.J., and S.W. Buol. 1998. Relationship of soil properties to parent material and landscape position in eastern Madre de Dios, Peru. Geoderma 83:143–166. doi:10.1016/S0016-7061(97)00133-X

Pitman, N. 2008. Unpublished. An overview of Los Amigos watershed, Madre de Dios, southeastern Peru. Available at http://cicra.acca.org.pe/espanol/paisaje_biodiversidad/los-amigos-overview9.pdf (verified 29 June 2011).

Räsänen, M., J. Salo, H. Jungner, and L.R. Pittman. 1990. Evolution of the western Amazon lowland relief: Impact of Andean foreland dynamics. Terra Nova 2:320–332. doi:10.1111/j.1365-3121.1990.tb00084.x

Räsänen, M., R. Neller, J. Salo, and H. Jungner. 1992. Recent and ancient fluvial deposition systems in the Amazonian foreland basin, Peru. Geol. Mag. 129(3):293–306. doi:10.1017/S0016756800019233

Rigsby, C.A., E.M. Hemric, and P.A. Baker. 2009. Late Quaternary paleohydrology of the Madre de Dios River, southwestern Amazon Basin, Peru. Geomorphology 113:158–172. doi:10.1016/j.geomorph.2008.11.017

Schildgen, T.F., K. Hodges, K. Whipple, P. Reiners, and M. Pringle. 2007. Uplift of the western margin of the Andean plateau revealed from canyon incision history, Southern Peru. Geology 35:523–526. doi:10.1130/G23532A.1

Soil Survey Staff. 2006. Keys to soil taxonomy. 10th ed. USDA-NRCS. U.S. Gov. Print. Off., Washington, DC.

Sombroek, W.G. 1966. Amazon soils: A reconnaissance of the soils of the Brazilian Amazon Region. Centre for Agricultural Publications and Documentation, Wageningen, the Netherlands.

Steffen, D., F. Schlunegger, and F. Preusser. 2009. Drainage basin response to climate change in the Pisco valley, Peru. Geology 37(6):491–494. doi:10.1130/G25475A.1

Tucker, G.E., and R. Slingerland. 1997. Drainage basin response to climate change. Water Resour. Res. 33:2031–2047. doi:10.1029/97WR00409

Uba, C.E., M.R. Strecker, and A.K. Schmitt. 2007. Increased sediment accumulation rates and climatic forcing in the central Andes during the late Miocene. Geology 35(11):979–982. doi:10.1130/G224025A.1