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Advancing Understanding of Hydrological and Biogeochemical Interactions in Evolving Landscapes through Controlled Experimentation at the Landscape Evolution Observatory

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CONTENTS

Abstract

Understanding the multitude of processes, feedback, and interactions among water, microbes, plants, and porous geological media is crucial for obtaining better predictions about the behavior of Earth's critical zone in the face of future climatic conditions. Current studies often suffer from the limitations of the spatial scale in which they are performed. By not considering the effects brought by the heterogeneity while moving from pore to landscape scales, important feedback and integrated behavior may be missed, rendering predicted behavior different from that of the natural systems. The time span in which such experiments are executed might also not be suitable for the observation of phenomena typically occurring over years in natural settings. Studying naturally occurring phenomena in situ carries with it the uncertainty about the initial state of the system, and the fact that observations require destructive sampling, which will interfere with the processes under investigation. The investigation of hydrological and biogeochemical evolution of natural systems is thus a challenging task for Earth scientists. The Landscape Evolution Observatory (LEO), a research facility managed by the University of Arizona and located at Biosphere 2, allows for the interdisciplinary investigation of the evolution of artificial hillslopes containing an initially naive mineral assemblage that will be subjected to controlled climate experiments. The LEO's unique set of instrumentation allows for exceptional observations of energy, water, and carbon fluxes across the three 330 m^3 hillslopes. Within the time frame of 10 years of interdisciplinary research, scientists will be able to address important questions related to the interactions among hydrology, geochemistry, and ecology. The LEO project maintains a database open to scientists and practitioners from different domains to address different research questions in a collaborative way. The research done at the LEO has the potential to be a milestone in terrestrial ecosystem research infrastructures.

4.1 Introduction

The physical, chemical, and biological structures and processes controlling reaction, flow, and transport in natural landscapes interact at multiple space and timescales and are difficult to quantify. Hence, the predictions of hydrological and biogeochemical responses to natural and anthropogenic forcing at the landscape scale are highly uncertain due to the effects of heterogeneity on the scaling of reaction, flow, and transport phenomena. The current paradigm of hydrological and geochemical theory is that process descriptions derived from observations at small scales in controlled systems (e.g., the Richards equation to describe flow in porous media; first-order chemical reaction kinetics to describe reactive transport) can be applied to predict system response at much larger scales (e.g., baseflow recession at the catchment outlet, landscape chemical denudation), as long as some "equivalent" or "effective" values of the scale-dependent parameters can be identified. However, this paradigm is known to be flawed (Sivapalan, 2005; Beven, 2006) and increasingly frequent calls have been made for new theories that will better link small-scale process understanding with large-scale predictions in space and time (Troch et al., 2009).

Furthermore, how natural systems evolve in time is difficult to observe in relatively short-term laboratory experiments or in natural settings, where landscape initial conditions and time-variant forcing (e.g., changing water and energy inputs associated with changing climate regimes) are unknown. The spatial structure of flow pathways along hillslopes determines the rate, extent, and distribution of geochemical reactions and biological colonization that drives weathering, the transport and precipitation of solutes and sediments, the further evolution of soil structure, and the biotic pallet that relies on it. With feedback among all components, the resulting evolution of structures and processes, in turn, produces spatiotemporal variability of hydrological states and flow pathways. Richter and Billings (2015), in their review of Tansley's "one physical system," highlight the need to understand these interconnected processes affecting evolution of natural systems, especially in Earth's critical zone. Therefore, an integrative approach to study hydrological, geophysical, geochemical, pedological, and ecological processes stands to enhance our knowledge of coupled aboveground and belowground Earth system processes (Richter and Billings, 2015).

Hydrologists and geochemists are well equipped to make quantitative predictions of dynamic responses in relatively simple systems across space and time (e.g., uniform hillslopes with homogeneous porous media cover on top of impermeable bedrock, weathering of basalt minerals under hydrological steady-state throughflow). However, the coevolution of hydrological and (bio)geochemical processes within even simple landscapes quickly renders these predictions less accurate. For instance, the first rainfall event on a hillslope covered with homogeneous ground basalt loamy-sand soil may lead to rapid chemical weathering of the silicate minerals and possible preferential precipitation of poorly crystalline hydrated solids. Such mineral transformation can then possibly lead to local variations in particle size distribution, total porosity, and associated hydraulic properties that dictate water flow. From purely mineral and abiotic conditions, spatially heterogeneous colonization of autotrophic and heterotrophic microorganisms as well as plant establishment can further enhance such mineral transformations and hence increase the overall heterogeneity of the hydraulic structure of the subsurface. The spatial distribution of microbial communities and vascular plants across the hillslope's extent may accelerate surface and subsurface structural development, making identification of hydraulic parameters at a hillslope scale required in our hydrological models an almost impossible task. What started off as a simple homogeneous system is quickly transformed into a complex coevolving landscape that makes quantitative predictions very challenging. The complexity increases when the question of scale is considered. Researchers across the realm of hydrology (Gleeson and Paszkowski, 2013), geochemistry (Molins et al., 2012), and biology (Fierer and Lennon, 2011) agree that perception of scale and its consequent impact on coupled-earth system processes affects the outcome of such interdisciplinary studies. It thus becomes a challenge to link small-scale processes occurring at a pore-scale to the large-scale processes occurring at a landscape-scale.

Linking pore-scale and landscape-scale processes is complicated in real-world settings because of poorly constrained impacts of initial conditions, climate variability, ecosystem dynamics, and geomorphic evolution. There is a need for experimental research to improve our understanding of hydrology–biogeochemistry interactions and feedback at appropriate spatial and temporal scales (Figure 4.1), larger than laboratory soil column experiments. This need served as primary motivation for establishing LEO at Biosphere 2, which offers a unique research facility that allows real-time observations of incipient hydrological and biogeochemical response under well-constrained initial conditions and climate forcing. The LEO hillslopes are the world's largest weighing lysimeters in a controlled environment and enables elucidation of the tight coupling between the time water spends along subsurface flow paths and geochemical weathering reactions, including the feedback between water flow and pedogenesis (Huxman et al., 2009). Prior studies of hillslope-scale aqueous geochemistry have been limited to soil-mantled landscapes that have evolved over geological timescales and whose contemporary weathering processes are largely controlled by that legacy. By initiating the LEO experiment—where three convergent hillslopes mantled by a relatively uniform homogeneous and isotropic basalt porous medium are subjected to aqueous geochemical weathering—we can, for the first time, explore the impacts of hillslope-length flow paths on incipient subsurface structure development. The facility and its instrumentation also allows closure of the water, carbon, and energy budgets at hillslope scales. In this

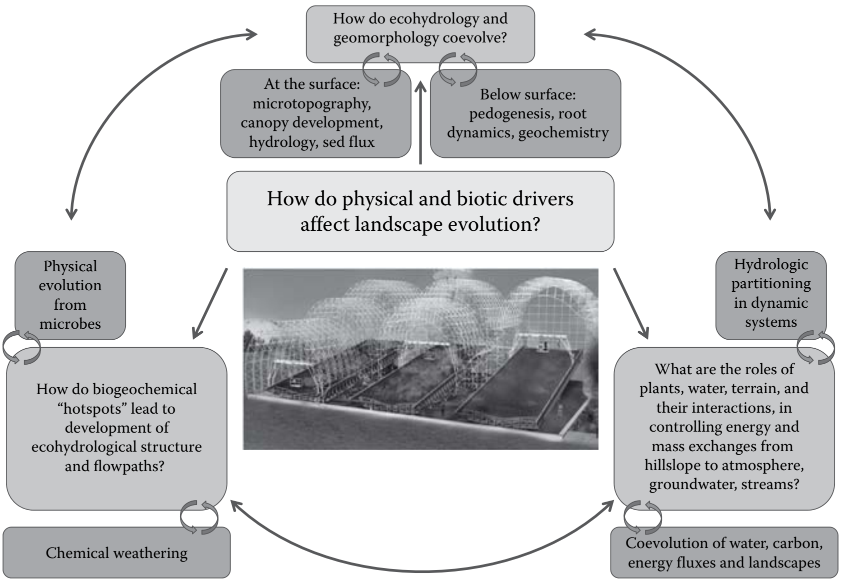


FIGURE 4.1
Conceptual framework for investigating the coevolution of life and Earth. The feedback among three principal guiding questions are central to this framework: geomorphology and ecohydrology; biogeochemistry and flow path development; and plant/water/terrain interactions with material and energy exchanges.

chapter, we discuss the infrastructural capability of LEO. We first provide a theoretical basis of LEO's instrumentation capability, followed by LEO's potential to study coupled hydrological and biogeochemical processes prevalent on a landscape scale. We conclude by highlighting long-term research goals of LEO and the consequent challenges faced, followed by a summary of LEO's unique place in terrestrial ecosystem research infrastructures.

4.2 Landscape Evolution Observatory: Description and Scope

4.2.1 The Landscape Evolution Observatory

The LEO consists of three constructed landscapes located within the climate-controlled Biosphere 2 facility of the University of Arizona, Tucson, USA (Figure 4.2a). They were designed to emulate features of zero-order basins, including a convergent topographic shape with an average slope of 10°. Maximum slope angles of approximately 17° (the angle is chosen because slope stability and hydrological response time; Hopp et al., 2009) are present near the convergence zone, located centrally with respect to the landscape

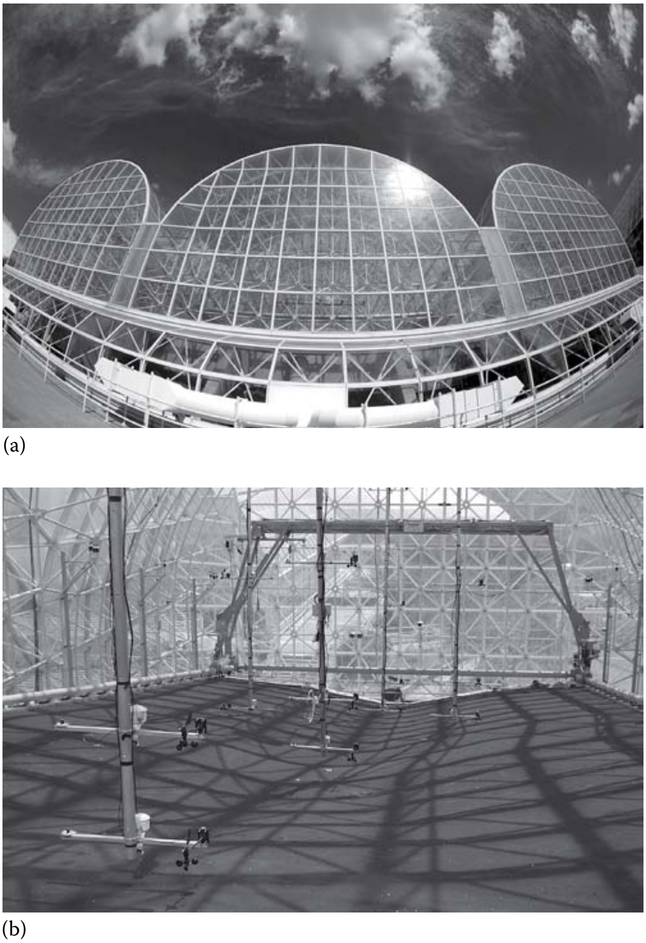


FIGURE 4.2
(a) Wide-angle photograph of the three climate-controlled bays of Landscape Evolution Observatory (LEO) at Biosphere 2, (b) Converging slope of the landscape, showing aboveground instrumentation.

width, and spanning more than half of the landscape length beginning from the downslope extent (Figure 4.2b). The convergent topography is expected to strongly control incipient coevolution of soil hydraulic, geochemical, and microbial properties, and ultimately the spatial organization of plant communities inhabiting the landscapes. The land surface is exposed to the interior atmosphere of the Biosphere 2 facility, which can be actively controlled to create specific combinations of air temperature, and wind speed—within some constraints (e.g., freezing temperatures would be cost-prohibitive, and wind speeds are limited by the flow-generating capacity of the air-handling systems). The ability to control the internal air temperature and wind speed implies that, within the stated constraint, a wide range of climatic conditions can be simulated and their effects studied. Technical details of the landscapes, sensors, samplers, instrument manufacturers, and expected precision can be found in Pangle et al. (2015).

The three LEO landscapes are experimental replicates; they have identical horizontal dimensions and nearly identical depth of parent material. Each landscape is filled with basalt tephra that was collected from a geologic deposit in northern Arizona, crushed to a loamy-sand texture, and packed to a uniform mean depth of 1 m. The packing was done by piling 30 cm of soil and compacting it to 25 cm, and repeated three times. The crushed basalt landscapes therefore represent a spatially uniform and abiotic initial condition (see also Dontsova et al., 2009; Pangle et al., 2015 for complete description of mineralogy and organic carbon content). The physical, chemical, biological, and topographical evolution of this parent material will be observed and manipulated through time. LEO is uniquely equipped to study integrated and spatially discrete measurements of (1) hydrological state and flux variables, (2) carbon cycling, (3) weathering, (4) photosynthesis and respiration, and (5) land-surface energy exchange. The facility is also capable of (1) conducting real-time isotopic measurement of water and carbon dioxide, (2) efficiently collecting and analyzing sample solutions, (3) conducting electrical resistivity tomography measurements of the landscape, and (4) detecting and monitoring spatial patterns of plant and microbial activity. In what follows, we briefly describe each of the variables noted earlier and their related theoretical basis in relation to LEO's research goals.

4.2.1.1 Integrated and Spatially Discrete Measurements of Hydrological State and Flux Variables

The water balance on the LEO landscapes is described as follows:

$$\frac{\partial S}{\partial t} = I(t) - E(t) - T(t) - Q(t) \tag{4.1}$$

where

- S represents water stored within the landscape (L^3)
- I represents irrigation inflow ($L^3\ T^{-1}$)
- E represents the evaporative loss of water from the land surface ($L^3\ T^{-1}$)
- T represents water loss from landscape to atmosphere due to transpiration ($L^3\ T^{-1}$) which is zero at present (when only bare soil exists)
- Q represents discharge of water through the seepage face at the downslope extent of the landscape ($L^3\ T^{-1}$)

All terms in Equation 4.1 can be measured as integrated, landscape-scale stocks and fluxes. Temporal changes in water storage within the entire landscape are monitored via 10 load cells that are installed within the steel support structure. Each load cell is under the only load-bearing points where the main slope is connected with the supporting structure. All other connections to the surrounding structure, the rain water lines, for example, have flexible connectors to reduce load bearing. Volumetric flow rates through the irrigation system are monitored with electronic flow meters, and the specific flux (L T^{-1}) and spatial patterns associated with each of the five independent irrigation circuits per landscape were measured through a series of manual calibration tests. The term *Q* encompasses both subsurface and overland flows of liquid water from the landscape. Subsurface seepage flows are routed through a plumbing system with in-line electronic flow meters and tipping bucket gauges. Those measurements are partially redundant, though also complimentary since each instrument yields optimal precision over a different range of measured flow rates. The seepage face boundary at the downslope extent of the landscape is partitioned into six subsections. To capture spatial variability of the flow—important during high flow conditions—each subsection is measured separately. Overland flow, if present, will be measured by routing the flow over a flume-like surface, through a plumbing system, and into an open basin with known dimensions, and with a pressure transducer continuously monitoring water depth. The combined flux of water vapor associated with *E* and *T* can be estimated at the landscape scale as the residual term of Equation 4.1.

Water does not move homogeneously through the soil matrix (Sivapalan et al., 2005; Troch et al., 2009), especially when plants are present. Root uptake will cause large differences in water content across a soil area, especially in the unsaturated zones (Volkmann et al., 2016a). In order to capture the spatial variability of the total within-slope water storage, the whole landscape-scale measurements of water storage and flux are complimented by spatially resolved measurements of several hydrological variables. The volumetric water content (L^3 T^{-3}) and water gauge pressure (kPa) are measured at 496 locations within each experimental landscape (Figure 4.3). These colocated measurements are recorded at 154 horizontal (*x*–*y* plane) locations and at 3–5 different depths (0.05, 0.2, 0.35, 0.5, and 0.85 m from the land surface) at each horizontal location. The sensor locations will provide a 1 m soil moisture content grid, which we deemed detailed enough to capture most spatial variability, but coarse enough to avoid creating a slope of sensors. The depth of the perched water table, when present, is monitored by 15 pressure transducers installed within bulkhead fittings that are sealed over drilled penetrations in the underlying steel structure (i.e., at the base of the soil profile; similar penetrations exist at the 154 horizontal locations, where the water content and pressure sensors are installed). Soil surface evaporation and plant transpiration are mainly determined by a vertical gradient of atmospheric vapor pressure deficit (VPD), which is a function of air temperature and humidity. Without atmospheric measurements, the evaporation (under the current bare soil conditions) would be the only undetermined term of Equation 4.1. To capture the atmospheric variability, a network of

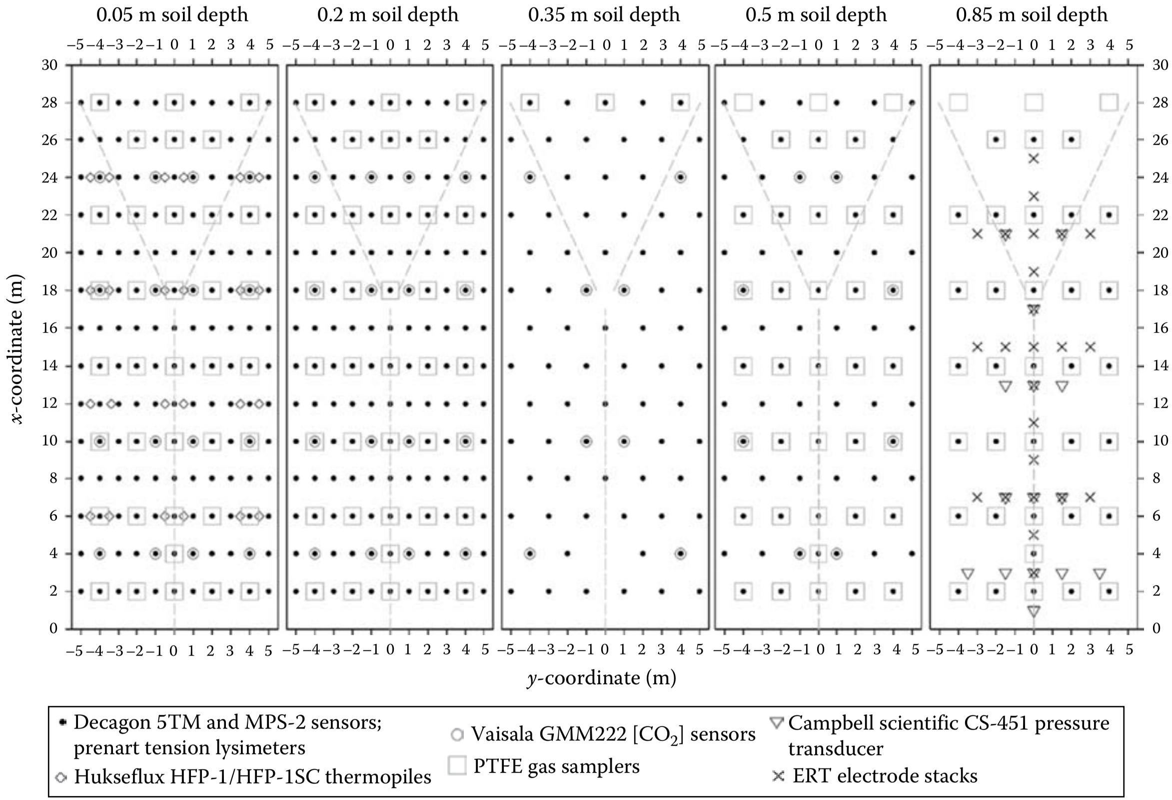


FIGURE 4.3
Diagram showing the lateral and vertical orientation of the sensor/sampler network in the LEO landscapes. For detailed description, refer to Pangle et al. (2015).

meteorological and gas sampling equipment has been installed onto vertically oriented aluminum masts that overhang each landscape. Field studies normally deploy Bowen ratio or Eddy covariance methods to determine the ecosystem carbon, energy, and water balance. However, the absence of strong above canopy mixing precludes the use of these techniques within Biosphere 2 (e.g., Arain et al. 2000). The five masts are mounted to the Biosphere 2 space frame and can be hoisted by winch, cable, and pulley system above the spray of the irrigation system to prevent dripping during experiments (Figure 4.2b). Since the atmospheric gradient will be driven by the surface exchange, we weighted the five heights on each mast stronger closer to the surface (0.25, 1, 3, 6, and 10 m above the land surface). At each height, air temperature, relative humidity, wind speed, and the water vapor concentration are measured—the former three by automated sensors, and the latter via pump-driven conveyance of air samples through a conduit system and to an infrared gas analyzer. These spatially stratified measurements, along with the closed-system nature of the Biosphere 2 facility, create additional opportunities for approximating whole-landscape evaporation based on mass balance calculations and for quantifying spatial heterogeneity of evaporative water flux (e.g., due to contrasting aspect).

4.2.1.2 Integrated and Spatially Discrete Measurements of Carbon Cycling, Weathering, Photosynthesis, and Respiration

The cycling of carbon within the LEO landscapes, and between the landscapes and atmosphere, is described as follows:

$$\frac{\partial C}{\partial t} = C_p(t) + C_a(t) + C_w(t) - C_r(t) - C_q(t) \tag{4.2}$$

where C is the mass of inorganic and organic (abiotic and biotic) carbon storage on or within the landscape (M). The subscripts attached to the carbon transfer rate terms on the right-hand side (M T^{-1}) represent carbon inputs/outputs to/from the landscape associated with precipitation p, photosynthetic assimilation a, weathering reactions w, autotrophic and heterotrophic respiration r, and water discharge from the landscape q.

The terms C_p and C_q can be quantified at the whole-landscape scale by measuring the total carbon content of inflowing irrigation water and seepage plus overland flow. Autosampling devices are in place to capture these water samples during all irrigation events on the landscapes. An on-site analytical laboratory is equipped to measure total, organic, and inorganic carbon in solution and in solid samples. A challenge for large-scale research infrastructures is to analyze huge number of samples generated at the facility. An on-site analytical laboratory proves to be advantageous here in terms of cost and time, since samples do not need to be sent out for analysis. This ensures efficient turnover time of sample analysis and reporting.

The terms C_a, C_w, C_r, and thus the derivative on the left-hand side (Equation 4.2) are approximated based on the spatial integration of distributed point-scale measurements. As mentioned in the previous section, atmospheric measurements are crucial in closing the carbon cycling budget. The aboveground network of gas sampling ports and infrared gas analyzer on the profiles, mentioned in the previous section, will be used to measure carbon dioxide (CO_2) concentration at approximately hourly interval. Atmospheric CO_2 profiles will allow for independent measurements of the whole slope carbon exchange (combined with periods of chamber closure), which is now inferred from within slope CO_2 measurements (see the following text), given the lack of autotrophic activity from vascular plants and the assumption that within-soil processes determine flux. Upon the establishment of plants, the combined soil and atmospheric profiles will be important in creating a net system flux spatially on the landscape. These measurements are complimented by estimate of stored carbon in solution and carbon exported with the solution at the seepage face.

The time resolution allows for the resolution of rapid changes following precipitation events or monitoring the expected diurnal patterns associated with radiation driving photosynthesis. The time derivative of the spatially weighted average of these measurements represents net ecosystem exchange of CO_2—the difference $C_a - C_r$, if the system is closed. At night, the same measurements represent only C_r. Those nocturnal measurements can be used to quantify functional relationships between air and/or soil temperature (measured at 25 and 496 locations, respectively) and ecosystem respiration, which, during daytime, can be used to decompose net ecosystem exchange of CO_2 into the C_a and C_r components (e.g., Phillips et al., 2011), and their source scales of spatial heterogeneity. It is well established that combinations of the approach mentioned earlier, use of CO_2 flux as a function of photosynthetically active radiation, and the periodic measurements of isotopic compositions of CO_2 flux (see the following text) provide good means for separating photosynthetic and respiratory process rates in time (Reichstein et al., 2005; Bowling et al., 2008; Lasslop et al., 2010). Additionally, 48 automated sensors measure CO_2 concentration in the soil gas phase; their spatial arrangement enables the quantification of concentration gradients within the soil, and between the soil and atmosphere, which can be used to estimate gas-phase CO_2 transfers into, and exiting from, the landscape (Barron-Gafford et al., 2011).

The carbon content of the soil solution can be monitored via 496 lysimeters that are colocated with the water content and pressure sensors (Figure 4.3) and connected to an automated vacuum system that enables relatively high-frequency sampling over the entire landscape (Section 4.3.3). These spatially and temporally intensive measurements of the soil solution carbon chemistry allow the measurement of total C storage on the landscapes and the calculation of carbon sequestration C_w. These measurements are also linked to measurements of lithogenic elements in solution that are indicators of weathering processes (Pohlmann et al.). Carbon and other solute concentrations are used further for rigorous parameterization of geochemical models that simulate the chemical evolution of the soil solid phase (Pohlmann et al.). The cumulative results of these models can be validated periodically by destructively sampling small cylindrical soil volumes that will be subsampled and analyzed to monitor inorganic and organic carbon sequestration and to determine changes in mineralogy of basalt matrix as a result of incongruent weathering using x-ray diffraction, x-ray absorption spectroscopy, and selective dissolution techniques. The same samples will undergo microbial DNA extraction, followed by high-throughput sequencing of the extracted DNA in order to determine diversity of rock-colonizing microorganisms.

4.2.1.3 Integrated and Spatially Discrete Measurements of Land-Surface Energy Exchange

The exchange of energy between the LEO landscape surfaces and their overlying atmosphere can be described as follows:

$$R_{si}(t) + R_{li}(t) + R_{so}(t) + R_{lo}(t) = H(t) + \lambda ET(t) + G(t) \tag{4.3}$$

where R terms represent radiant energy fluxes specifically associated with shortwave and longwave (s and l) radiation that is incoming or outgoing (i and o) to or from the landscape. Terms on the right-hand side represent sensible heat flux H between land and air, λET—the product of the latent heat of phase transition and the magnitude of evaporation plus transpiration, and conductive heat transport and storage into the landscape, G.

Latent heat flux is the only term in Equation 4.3 that is measured at the landscape scale, that is accomplished using the whole-landscape ET estimates, based on load-cell measurements and mass balance calculations, and the known value of latent heat of vaporization. The radiant flux terms on the left-hand side of Equation 4.3 are measured directly by a pair of four-way net radiometers that are located at 1 m height above the soil surface on the masts located over the east- and west-facing hillslope segments adjacent to the convergence zone (Figure 4.2b). Uncertainties exist in using these point measurements to represent the average at the landscape scale due to the impact of the windows and frames of the climate-controlled bay (Figure 4.2a) on solar radiation and mismatched source areas. The conductive heat flux into the ground G is measured directly by heat flux plates at 24 locations (0.08 m depth, with associated thermocouples buried at approximately 0.02 m). Those devices are arranged in uniform grid spanning most of the land surface (Figure 4.3). Finally, the sensible heat flux from land to atmosphere H can be approximated as the residual component of Equation 4.3 or possibly through application of modified gradient-flux methods that would utilize the aboveground array of meteorological instruments described earlier.

4.2.1.4 Remote Sensing of Mass and Energy Fluxes

The landscape surface is the exchange interface of carbon, energy, and water fluxes and thus warrants an even greater spatial resolution of the measurements. Remote sensing techniques can image the surface at sub centimeter resolution and thus provide detailed information on the spatial heterogeneity of evaporation (thermal imaging), water content (hyperspectral imaging), surface chemistry (potential salt precipitation during evaporation; hyperspectral imaging) on the bare soil and leaf temperature (a potential proxy for transpiration, photosynthesis, and leaf respiration; thermal imaging), and photosynthesis (hyperspectral imaging). One key challenge of remote sensing is colocation, both spatially and temporally, of the collected images, especially since no camera exists that can capture the full slope with the height constraint created by the structure. To resolve this, we mounted a 36 m long aluminum track system, including a motor-driven circulating belt with an attached climate-controlled container, below the space frame and at a constant 7 m height above each landscape. To provide greater temporal resolution and to reduce man-hours in mounting and dismounting the camera systems, one infrared imaging system and one visible-to-near-infrared hyperspectral imaging system are located within a climate-controlled box on each track system. The imaging systems and box can be rapidly and very precisely (~1 mm along path resolution and repeatability) moved along the track system, which spans the entire length of the long axis of the landscapes. Within the climate-controlled box, each imaging system is mounted on a motor-controlled rotating axle rod, which enables panning to three different angles and ultimately the integration of multiple images to provide full field-of-view coverage of the entire width of the landscape. The infrared imaging system will provide centimeter-scale image resolution, and the resulting data arrays can be used to approximate E and λE at the landscape scale via novel methods demonstrated by, for example, Shahraeeni and Or (2010). The hyperspectral imaging system is intended to enable landscape-scale estimates of C_a through novel and still experimental methods, discussed by, for example, Meroni et al. (2009).

4.2.2 Fast, Real-Time Isotope Measurement of Water and Carbon Dioxide with State-of-the-Art Laser Spectroscopic Instrumentation and Whole-Slope and Atmospheric Sampling System

A keystone to achieving the declared goal of characterizing and understanding the interactions between hydrological and biogeochemical processes is to be able to determine the pathways and residence times of water and CO_2 through the LEO landscapes and atmospheres. Both molecules are of interest by themselves with regard to understanding water resource availability and climate change but are also critical reagents for the weathering and biological colonization processes and coevolving patterns. However, measurements of states and whole-system in- and outputs of bulk water and CO_2 (see previous sections) cannot provide the required information on sources, pathways, and time spans available for chemical reactions to take place. Stable isotope analysis, in turn, is well suited for tracking fluxes and reaction processes of water and CO_2 through landscape and atmosphere (Gat, 1996; Yakir and Sternberg, 2000; Bowling et al., 2008) and can be integrated with modeling (Sprenger et al., 2015; Scudeler et al., 2016). Its application to meet the research needs at LEO is, however, challenging. While conventional isotope methodology is expensive and destructive, the space–time scales of the experiment and the highly dynamic processes under investigation demand an enormous amount and a high frequency of measurements to be performed without significantly disturbing the coevolving landscapes.

To meet the task of measuring isotope abundances associated with both water and CO_2 pools across LEO at high frequency, a state-of-the-art isotope laboratory is being implemented that makes intensive use of recent developments in laser-based analyzing (e.g., Baer et al., 2002; McManus et al., 2015) and in situ field sampling techniques (e.g., Sturm et al., 2012; Volkmann et al., 2016b). Two different isotope analyzers based on laser absorption spectroscopy (LAS) were selected. The first LAS instrument is a near-infrared gas analyzer based on off-axis integrated cavity output spectroscopy (OA-ICOS; IWA-35EP, Los Gatos Research Inc., Mountain View, CA, USA) for measurement of the hydrogen ($\delta^2H–H_2O$) and oxygen ($\delta^{18}O–H_2O$) stable isotopic composition in injected liquid water and water vapor. The second LAS instrument is a trace gas analyzer based on quantum cascade laser absorption spectroscopy (QCLAS; TILDAS-D, Aerodyne Research Inc., Billerica, MA, USA), which measures $\delta^2H–H_2O$ and $\delta^{18}O–H_2O$ and the carbon ($\delta^{13}C–CO_2$) and oxygen ($\delta^{18}O–CO_2$) isotopic composition of CO_2. Detailed descriptions of the respective technologies and instruments can be found elsewhere (Baer et al., 2002; Nelson et al., 2008; Tuzson et al., 2008; McManus et al., 2015). To facilitate stable and uninterrupted operation of the analyzers directly on-site, a custom on-site containment room was constructed below the central LEO hillslope and equipped with air-conditioning and UPS power supply. This on-site laboratory provides time-efficient analysis of the samples.

The OA-ICOS instrument will be used mainly for automated high-frequency sampling and analysis of seepage water outflow from the three LEO hillslopes. It will therefore be paired with a multiport liquid sampling system (Los Gatos Research Inc.) as described by Pangle et al. (2013). This setup was chosen because it is robust and will facilitate isotopic analysis of outflow from the three LEO hillslopes at intervals of approximately 30 min (Pangle et al., 2013). The half-hourly interval was considered sufficient to capture most of the discharge isotope dynamics associated with variable water flow path activation and transit times through the landscape given that hillslopes such as those comprising LEO act as low-pass filters to any variable input signal. Thereby, our setup should allow for reliable association

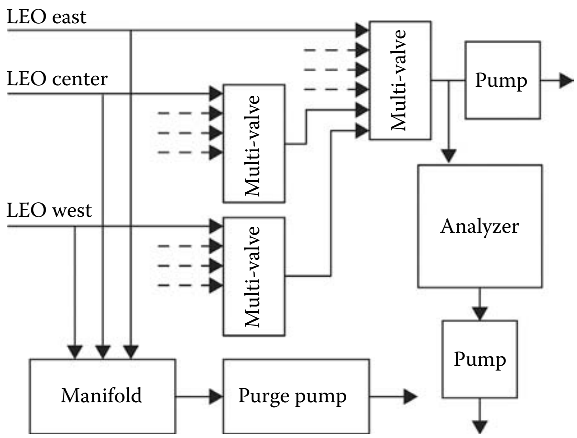


FIGURE 4.4
Schematic of the planned setup (simplified) for direct monitoring of stable isotope abundances in atmospheric water vapor and/or carbon dioxide using a laser spectroscopic analyzer at the LEO. Only 1 out of 24 available intake lines is shown for each LEO bay.

of water pathways with solute export resulting from biogeochemical processes at relevant timescales and detail.

The QCLAS instrument will be used mainly for continual monitoring of the isotopic composition of atmospheric as well as soil air CO_2 ($\delta^{13}C–CO_2$, $\delta^{18}O–CO_2$) and water vapor ($\delta^2H–H_2O$ and $\delta^{18}O–H_2O$). In each LEO hillslope, 24 atmospheric air intake lines are available, with inlets at four to five different heights (0.25, 1, 3, 6, and 9–10 m) along each of five masts distributed over the slope surface (Figure 4.4). Subsequent sampling of the intake lines will be facilitated by stream selector valves located at the on-site isotope laboratory, with flow driven by a downstream vacuum pump (Figure 4.4). To reduce the time delay associated with gas transport from air inlet to analyzer, the intake lines upstream of the valves will be constantly purged with fresh atmospheric air using branch-off lines connected to a purge pump via manifold unions (e.g., Sturm et al., 2012).

To sample soil air for direct isotopic analysis, arrays of 151 custom sampling probes will be used that are installed along vertical profiles (0.05, 0.2, 0.35, 0.5, and 0.85 m from the land surface) within each of the model landscapes at LEO (Figure 4.3). A multivalve control system will be set up to sample automatically from the various probe locations using a closed flow-through loop approach. These measurements will not only provide insights into gas-phase fluxes and interactions such as CO_2 diffusion and consumption during weathering or evaporation; since soil temperatures are measured throughout the LEO soils, inference of the liquid water isotopic composition in the landscape's subsurface is also possible based on the soil water vapor-phase measurements (Volkmann and Weiler, 2014) due to the mainly temperature-dependent isotopic liquid–vapor equilibrium in soils

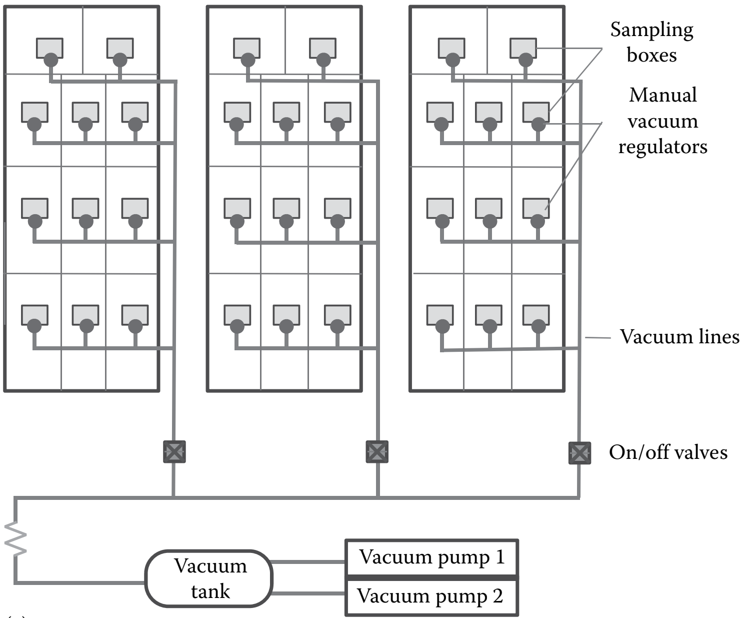
(Mathieu and Bariac, 1996). These measurements can then be used to infer flow pathways and interaction times of water throughout the hillslopes. The anticipated sampling interval is <5 min per probe location. The system will thus allow for approximately one complete measurement cycle per day, but subsets of the available soil gas probes will be selectable to attain much higher temporal resolution at selected profiles sufficient to capture even rapid processes such as preferential infiltration (Volkmann et al., 2016a). Despite the unprecedented capabilities, spatial and temporal resolution must, however, clearly be traded off with regard to the isotopic measurements.

4.2.3 Solution Collection and Analysis

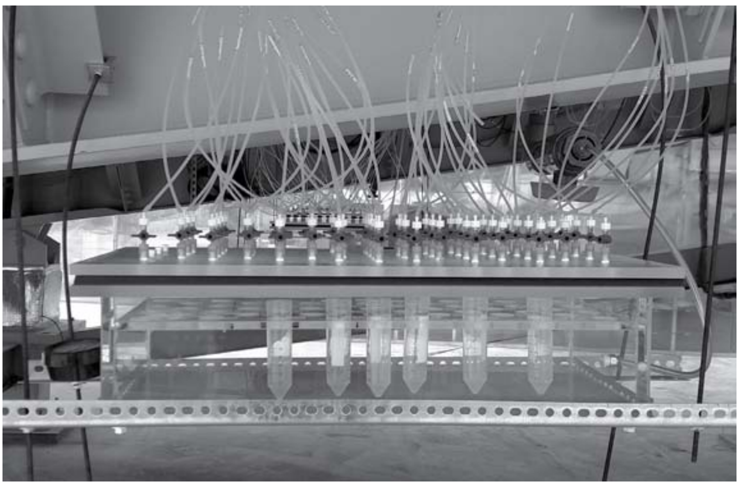
The fate of organic and inorganic carbon in the soil and incongruent weathering of basalt matrix, as well as translocation of carbon and lithogenic elements on the slopes will be tracked using a combination of solution sampling and periodic coring of the soil matrix. This allows us to map carbon accumulation in soil solution and solid phases and to trace lateral flux of carbon through the soil. It also allows to identify changes in mineralogical and chemical composition of basalt as a result of dissolution of primary minerals, movement of resulting solutes through the slope, and precipitation of secondary minerals. Solution sampling will be performed through 496 samplers by Prenart samplers (Frederiksberg, Denmark) that are embedded in LEO at the same locations as moisture and water pressure sensors described in Section 4.2.1. A sampling line connects colocated Prenart samplers to 11 custom-designed sampling modules (Figure 4.5). Each sampling line has individual on/off valve. Modules consist of a Plexiglas vacuum box equipped with manual pressure regulator, vacuum gauge, and a tray capable of holding fifty-five 50 mL centrifuge tubes for sample collection, connected to a vacuum manifold. Vacuum is supplied by two single-stage rotary vane vacuum pumps common for all three slopes and located outside of the LEO area.

The vacuum system allows collection from all 496 samplers on each slope at the same time. However, when needed, the vacuum could be applied to each module or even each sampler separately, allowing sampling a section of each slope at a time as the wetting front progresses. Suction to be used in each module can be determined by water potential measured by the sensors colocated with solution samplers to ensure sufficient suction to withdraw a sample, but not high enough to withdraw solution outside of the immediate sampler vicinity and create new preferential flow pathways.

Samples will be regularly collected from all active samplers in a given hillslope and archived at –80°C. We will also collect water samples from rainfall and outflow (seepage flow and possibly some overland flow). The analytical laboratory on-site is equipped for high-throughput sample analysis for major cations and anions with capability for concurrent analysis of cations and anions, including autosampler, capillary and analytical pumps, two conductivity detectors, and eluent generators for both pumps. Electrochemical



(a)



(b)

FIGURE 4.5
(a) Schematics of solution sampling module. Each hillslope will be equipped with 11 solution sampling modules. Modules include a vacuum box (b) with up to 55 sample containers connected to a vacuum line through a vacuum regulator. 496 Prenart samplers that are embedded in each LEO slope are connected through the sampling lines to the containers in the box. Vacuum is maintained through a dual pump and storage tank.

detector and a column are also available to analyze solutions for carbohydrates and amino acids; dissolved organic and inorganic carbon, and total dissolved nitrogen (Shimadzu TOC-L Series Total Organic Carbon (TOC) and nitrogen analyzer equipped with autosampler for water samples (TOC-LCSH), and an SSM-5000A unit for analysis of solid samples); and pH (VWR® sympHonymultimeter), which is necessary to determine inorganic carbon speciation in solution.

4.2.4 Electrical Resistivity Tomography

Geophysical methods have the potential to overcome limitations in spatial resolution of local point measurements, being able to measure subsurface structures and to estimate flow and transport in a minimally invasive or even noninvasive way (Vereecken et al., 2004). Among current geophysical methods used for monitoring subsurface hydrological properties, electrical resistivity tomography (ERT) has found great acceptance. Electrical resistivity within the soil can be correlated to several physical and chemical soil properties such as soil salinity, temperature, clay content, soil-water content, and solute concentration. Several studies have applied the ERT technique for obtaining high-resolution monitoring of spatial/temporal solute transport in controlled infiltration and tracer experiments (Binley et al., 1996, 2002; Slater et al., 2002) as well as in vadose zone soil water monitoring (Michot et al., 2003; Nijland et al., 2010; Beff et al., 2013). A typical ERT application consists of injecting a low-frequency electrical current through a pair of electrodes and measuring the potential at other electrode pairs. This procedure is repeated several times, with different injection locations, so that a set of redundant measured potentials is obtained, which will give rise to a distributed image of apparent electrical resistivity. The apparent electrical resistivity is further transformed into "true" resistivity through an inversion procedure (Vereecken et al., 2014).

A custom array of 24 potential-measuring electrode stacks was built inside each LEO hillslope prior to soil packing. A compromise between costs and resolution was made when installing the ERT sensors in order to arrive at the achievable resolution for electrical resistivity of nanometer scale. Each electrode stack comprises a hollow insulating acrylic cylinder, where a sequence of five stainless steel electrodes separated by different distances is placed (Figure 4.6). Each electrode stack is connected to a centralized device that fires current, reads the potential differences, and stores the results. The electrode stacks are equipped to read several potential combinations between electrodes across the hillslope, therefore, providing images of apparent electrical resistivity, which can then be interpreted after inversion algorithms are applied.

The ERT system is of importance to the LEO project, because of its key role in supporting cross-discipline research endeavors. The ERT three-dimensional scans associated with hydrological models through coupled

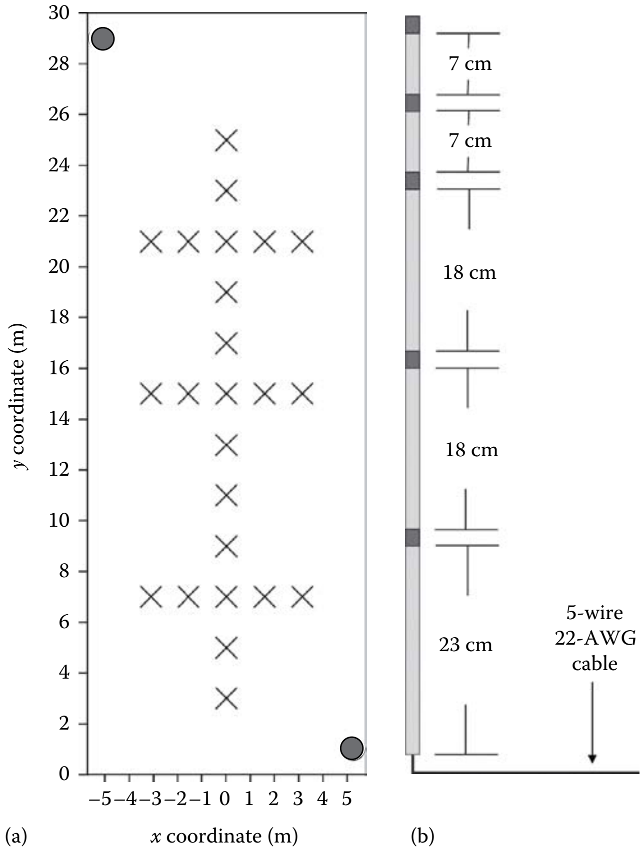


FIGURE 4.6
(a) Plan view of the LEO landscape dimensions. X symbols mark the position of potential-measuring electrode stacks. Circles mark the position of the current-injecting electrodes. (b) Diagram of potential-measuring electrode stacks: dark gray indicates stainless steel electrodes, while light gray indicates the insulating acrylic rods.

hydrogeophysical inversion (Ferré et al., 2009) will provide a continuous feed of high-resolution imaging of the flow processes at the subsurface as the LEO landscapes evolve from initially homogeneous crushed basalt rock into a complex ecosystem. Assessing evolution of flow processes within the subsurface in a spatially distributed manner is key to interpreting results of soil and water chemistry analysis along LEO's evolutionary path. Describing the location, quantity, and velocity of water flowing within the landscape at the same time that its chemical composition is being investigated, will allow investigation of feedback and interactions between coupled hydrological and biogeochemical processes. Additionally, ERT-generated data will aid the development of novel hydrogeophysical inversion methods, enabling the real-time monitoring and visualization of the movement of water, solutes, and assimilated fields of soil hydraulic properties.

4.2.5 Detection and Monitoring of Microbial Activity

In the natural world, soil and landscape dynamics are influenced by the interaction of physical, chemical, and biological processes. The organismal diversity of a site, inclusive of vascular plants, soil microorganisms, and burrowing and soil disturbing fauna, all contribute to the life–environment interactions that play a crucial role in formation of soil structure and biogeochemical cycling of nutrients. In the context of a landscape being colonized by life, microorganisms are important early pioneers that can have large impacts on nutrient cycling and through symbiosis can influence plant establishment and growth. Combined, these processes affect a number of ecosystem processes, such as net primary production, which dictates the degree to which biology may influence the evolution of a physical landscape. Consequently, during the progression of a parent material developing into soil over a landscape scale, one of the first biological features to consider is how microbial life at the microscale evolves and impacts the macro hillslope scale when subjected to varying climatic and relief conditions. Such questions of how these microbiological systems influence the physical template will be important to the continuing sequence of experimentation in LEO, where understanding plant impacts on the water balance, for example, represents another opportunity to evaluate life–environment couplings important to understanding Earth system science.

While LEO has been extensively used to study hydrological and geochemical interactions at the hillslope scale so far, the infrastructure will also allow researchers to study the diversity of microbial communities capable of exploiting the extreme oligotrophic conditions of a basalt rock hillslope and identify key environmental variables that significantly influence the diversity and activity of these communities. The basaltic soil material of LEO has low organic matter content (Pangle et al., 2015), and the absence of vegetation on the hillslopes during initial phases of the experiment eliminates the possibility of carbon input from plants. The progression of microbial life on LEO slopes is projected to be monitored from time zero through a 10-year period during which the slopes are expected to experience primary mineral weathering, release of lithogenic elements followed by secondary mineral formations. Coupled with the gradient and alternate wetting–drying of the hillslopes, a heterogeneous presence and variability of microbial occurrence across the LEO landscape is expected. It will be interesting to observe diversity patterns along the slope at multiple scales, particularly keeping in mind that species diversity in ecological systems is composed both of point estimates of species richness (what kinds), evenness (how many), and spatial patterns of heterogeneity (site-to-site turnover; Sengupta and Dick, 2015). Of particular interest are correlations between species richness of microbial communities at sample spots and the associated flow dynamics and porewater geochemistry. Modern functional genomics will enable similarly coordinated measures of aspects of gene diversity (functional diversity) in the same context (e.g., Allison and Martiny, 2008).

Previous research has shown the presence of microorganisms in basaltic material. Rogers and Bennett (2004) reported the release of limiting nutrients from silicates by subsurface microorganisms while a study by Savostin (1972) suggested the presence of "silicate microorganisms" capable of growing on silicates in absence of organic substances. Recently, Orcutt et al. (2015) provided empirical evidence of chemoautotrophic carbon fixation by basalt-hosted microbial communities in the deep ocean environment. These findings suggest that even in oligotrophic mineral environments like the LEO slope, one can expect to find microbial life adapted to functions. The characteristic mineral composition of the LEO soil material, along with low organic matter input, can be considered as a primary ecosystem capable of harboring pioneer microorganisms with mineral-weathering abilities.

The specific challenges posed by the LEO experiment include the development of protocols to characterize the low-biomass samples that we predict will be present at time-zero in the basalt soils and the design of nondisruptive sampling strategies that will produce a suite of samples representative of the range of microenvironmental conditions present across the surface and depth of the hillslope. Using microbial DNA environmental sampling and next-generation sequencing techniques (see Chapter 8), researchers have been able to detect microbial life at regions of low biological productivity. A few of these include bacterial diversity in arid soils of the Atacama Desert, Chile (Drees et al., 2006; Neilson et al., 2012), microbes colonizing subsurface calcite cave formations in Kartchner Caverns, AZ (Ortiz et al., 2013, 2014), and microbial communities of acid-generated mine tailings (Valentín-Vargas et al., 2014). Generally, current sequencing techniques like Illumina® require minimum DNA concentration of 1 ng/μL to generate a community DNA library. However, the amount that can be retrieved from oligotrophic environments falls in the picogram range. Research groups in the Department of Soil, Water, and Environmental Science, University of Arizona, have expertise working on isolating microbial DNA in oligotrophic environments. Protocols have been developed to obtain sequence reads from 0.1 ng/μL DNA extracts (Valentin-Vargas et al., 2014), and research continues to further optimize library preparation from lower concentration DNA extracts. Currently, sampling protocols are being developed to recover samples from the LEO surface without introducing any exogenous microbial contamination. Due to the extremely low biomass levels present in the LEO landscape, slight contamination from sampling equipment or technicians can have a profound impact on the sample taxonomic profiles. The highly instrumental and environmentally controlled LEO facility provides an excellent opportunity to develop new protocols for microbial community analysis, developing trait-based approaches to representing microbial communities and integrating data generated into cutting-edge models that predict the impact of in situ microbial activity on micro- to macroscale environments (e.g., Allison, 2012; Wieder et al., 2013).

4.3 Research Foci to Advance Understanding of Interacting Hydrological and Biogeochemical Processes

4.3.1 Flow and Transport Studies at Landscape Scales

In recent years, there has been a paradigm shift in our understanding of flow and transport at watershed scales and approaches to their prediction. The complexity and heterogeneity of water movement within individual landscape units have been recognized in hillslopes (Jencso and McGlynn, 2011; Nippgen et al., 2011), riparian areas (Buttle et al., 2004; Detty and McGuire, 2010) and within streams and their hyporheic zone (Bencala et al., 2011). This has led to calls for new approaches to prediction that go beyond the traditional continuum models (i.e., Richards equation and the St Venant equations for flow and convection–dispersion/diffusion for transport—or approximations thereof) (Sivapalan, 2005; Beven, 2006; Kirchner, 2006; McDonnell et al., 2007), as these generally rely on calibrated "effective" property values to replace the spatially distributed properties of the landscape—those are essentially unknowable at catchment scales using current technology.

New approaches have sought ways to represent flow and transport directly at the scales of interest, with the expectation that the new equations may be "different in form, not just different in the parameters" (Kirchner, 2006) than the continuum-scale equations. The concept of a representative elementary watershed, or REW (Reggiani et al., 1998, 2000, 2001; Beven, 2006), provides a conceptual framework for representing flow through individual landscape elements within an REW and in a river network based on a rigorous time–space averaging of the conservation laws governing mass, energy, momentum, and entropy. These equations are not complete, however, as they require specification of "closure relations" that specify the boundary fluxes exchanged between these landscape elements in terms of their states (storage, fluxes, other boundary forcings) and parameterized by measurable properties of the landscape. These closure relations must represent the aggregate effect of the unresolved "sub-REW" heterogeneities and flow complexity without resolving them explicitly, and they have been termed the "Holy Grail" of scientific hydrology (Beven, 2006).

The understanding and prediction of the timing and partitioning of fluxes of water at landscape scales is a considerable challenge on its own, but the understanding and prediction of transport at watershed scales is an even greater challenge. Studies of using passive tracers present in precipitation (such as chloride and water molecule isotopologues) have shown that a large fraction of the water that appears in a stream in response to a storm is water that has been present in the catchment for a considerable period of time (Sklash and Farvolden, 1979; McDonnell, 1990; McDonnell et al., 2010). This water reaches the stream through a flow system that includes spatially variable infiltration and unsaturated flow (Roth, 1995), shallow transient lateral flow through perched water tables (Troch et al., 2003), preferential flow pathways that connect and disconnect uplands and riparian areas with threshold nonlinearities (Tromp-van Meerveld and McDonnell, 2006a; Jencso and McGlynn, 2011), flow through deep and shallow fractured bedrock (Montgomery and Dietrich, 2002), and other types of fine-scale dynamics (Tetzlaff et al., 2008). The challenge has been to find ways to represent the mixing of water of different ages in the discharge that agrees with observational data and accounts for the highly transient, complex nature of the transporting flow. These efforts are ultimately aimed at a complete theory of flow and transport at watershed scales suitable for use in predicting transport of solutes, contaminants, and pathogens through complex landscapes (Kirchner et al., 2000; Rinaldo et al., 2011; van der Velde et al., 2013).

Understanding the hillslope-scale structural controls on flow and transport is one of the two main research questions that LEO was built to address (Hopp et al., 2009). The LEO facility has been built to allow us to develop observations of the "closure relations" governing flow and transport at a scale approaching that of real hillslopes in a highly controlled laboratory environment. These hillslopes can be subjected to artificial rainfall events, and the subsequent flow and transport can be analyzed by over 1800 sensors and water samplers embedded in each hillslope. Analysis of deuterium and oxygen-18 stable isotope tracers can be conducted in real time using existing laser spectroscopic instrumentation. Insights obtained from the flow and transport studies can be applied to coupled biogeochemical processes occurring on the hillslope, as described in Sections 4.3.2 and 4.3.3. This forms an integral part of the second research question attached to LEO: that of landscape stabilizations and ecosystem development over time. This includes the role of biological processes and the impact of life–environment interactions. While microorganisms have soil-stabilizing properties and impact biogeochemical cycling of nutrients, vegetation controls net primary production, the order of magnitude of life in a location, along with affecting flow and transport in natural landscapes: through root-water uptake and redistribution over timescales of minutes to days; through biomass growth and canopy development over days to seasons; through the formation of preferential flow paths over weeks to years; and through controls on soil structure and geochemical weathering over years to millennia.

4.3.2 Coupled Hydrological and Geochemical Process Evolution

There exists a tight coupling between the time water spends along subsurface flow paths and geochemical weathering reactions (Steefel, 2008; Maher, 2011). Since mineral dissolution is kinetically limited, the duration of water contact time with matrix minerals along a given flow path determines the extent to which it acquires solutes from mineral dissolution and, hence, the *relative saturation* of mobile solution with respect to primary mineral dissolution and potential secondary mineral formation (Maher et al., 2009). Such reactions are especially rapid in extrusive, mafic igneous rocks such as basalts (Gislason et al., 2008). Incongruent dissolution of primary silicates to form poorly crystalline hydrated solids, as well as crystalline layer silicate clays and (oxyhydr)oxides, can affect these rates (Yokoyama and Banfield, 2002), as can the presence of complexing biogenic ligands (Neaman et al., 2005; Dontsova et al., 2014). Progressive weathering and its distribution in space leads to the development of subsurface heterogeneity (e.g., catena development), which, in turn, feeds back to affect water flow paths (Dontsova et al., 2009).

As chemical weathering drives the particle size distribution to smaller values and hydrated solids are formed, this will affect the pore size distribution, hydraulic conductivity, and hence the water transit time distribution along these flow paths (Li et al., 2008; Pacheco and Van der Weijden, 2012). Changes in particle size, surface chemistry, and porosity distributions further alter reactive interfacial area and weathering rates of the soil medium (Anbeek, 1992; Brantley and Mellott, 2000), with associated feedback on subsurface flow path evolution, bio-colonization, and nutrient and organic matter retention. At the same time, changes in flow paths and transit time distributions will affect geochemical weathering reactions through alterations of Gibbs energy of reaction (e.g., changes in the quotient of product and reactant activities relative to equilibrium) (Ganor et al., 2007). These geochemical–hydrological couplings are considered fundamental to the evolution of subsurface structure in the critical zone (Chorover et al., 2007).

Dontsova et al. (2009) used a reactive transport geochemical model coupled with a hillslope-scale hydrological model and pedotransfer functions to predict mineral transformations in a basalt soil representative of LEO (45.67% basaltic glass; 35.87% labradorite, feldspar; 11.94% forsterite, olivine; 6.53% diopside, pyroxene) and to estimate resulting changes in soil hydraulic properties. They found that significant changes in both the fraction of secondary minerals and predicted hydraulic conductivity are expected after 10 years of climate forcing representative of semiarid Southwestern United States and that observable changes are expected as early as within 3 years. Model results indicated that characteristic spatial trends in pore water chemistry, indicative of the trajectory of soil formation, arise even during initial hydrological events, well before changes in porous media solid-phase composition are likely to be detectable. It remains to be tested whether these model predictions are realistically capturing the time evolution of subsurface structure related to geochemical weathering and precipitation.

The geochemical evolution predicted by this modeling varied spatially in a way that reflected the variations in hydrological function between different parts of the hillslope. Differences in soil moisture and residence time between the unsaturated upslope areas and the persistently saturated convergent regions produced significant structure in the subsurface hydraulic heterogeneity, consistent with observations in pedogenic studies along catenas and chronosequences (Chadwick and Chorover, 2001; Jing et al., 2008).

The LEO facility will allow us to simultaneously measure soil moisture status and the associated residence times of water within the slopes, as well as the geochemical transformations that take place during and after rainfall–runoff events by chemical analysis of soil solution samples drawn from the network of soil samplers (described in Section 4.2.3). Water collections from early rainfall experiments at LEO in 2013 provided insight into the nature and distribution of secondary mineral phases formed following incipient weathering of the primary basalt material (Pohlmann et al., 2016). Samplers embedded in the 1 m profile conveyed pore water for individual collection beneath the steel frame of the hillslope. Over 900 pore water samples collected from two distinct rain events were processed and analyzed for a suite of geochemical analysis including anions, cations, inorganic carbon, and pH. Sensors also recorded the volumetric water content and temperature associated with each of these pore water samples. Initial processing and analysis for a selection of samples following the first rain event revealed solid formation in the colloidal size range (60–2000 nm) for aluminum (Al), phosphorus (P), and iron (Fe). This suggests the development of poorly crystalline mineral phases such as gibbsite (an Al hydroxide) and ferrihydrite (an Fe oxyhydroxide), in addition to phosphate (a common P-bearing anion) known to associate with such minerals. These tiny solids represent the earliest stage of soil development from our essentially unweathered basalt (Pohlmann et al.).

4.3.3 Microbiological and Biogeochemical Evolution of Landscape

Earth's land surface is the locus for coevolution of biota, soils, and landforms and is governed by processes important to soil science, geomorphology, hydrology, ecology, and atmospheric sciences (Showstack, 2012). The processes are coupled in terms that the functioning and dynamics of one affects that of the other. In the context of a colonizing landscape, microbes are at the forefront of the biotic component of landscape evolution. They play a significant role in bioweathering of minerals during soil genesis through the oxidation of primary minerals, the influence of acid-generating metabolisms that increase solubilization rates, and the production of siderophores and other organic molecules that function as metal-complexing agents to drive weathering reactions (Mapelli et al., 2012). However, interpreting microbe–mineral interactions with underlying hydrological forces raises a few fundamental questions. Focusing on geochemistry, one can ask whether microorganisms benefit by the dissolution of a mineral or if weathering is simply a coincidental by-product of basic biochemical functions. With respect to hydrology, one can question the effect of hydrological partitioning and water-transit time distribution on microbial evolution of the landscape, and conversely, the effect of microbial evolution on time-dependent change in flow paths. The answers to these questions cannot be answered by studying microbial communities in isolation. Instead, studies that focus on microbial ecology, that is, interaction of microorganisms with each other and their environment are a key variable to the landscape evolution equation.

Microorganisms colonizing bare basaltic material can potentially be categorized into three metabolic groups: (1) *chemolithoautotrophs* that obtain energy through the oxidation of diverse reduced (often mineral-bound) elemental forms (i.e., Fe, Mn, and S), thus oxidizing the inorganic element and generating acid as a by-product; (2) *phototrophic cyanobacteria and algae* that fix CO_2 and N and function as drivers of increased biodiversity in oligotrophic systems; and (3) *heterotrophic bacteria or fungi* that oxidize available organic C supplies and produce extracellular products that solubilize primary or secondary minerals and can function as complexing agents that influence pore water chemistry. In addition, microbial respiration increases soil pore CO_2 concentrations leading to enhanced pore water concentrations of carbonic acid and associated (carbonation) weathering reactions.

With the accretion of organic C from chemoautotrophic growth, heterotrophic colonization is expected to ensue. Literature suggests that the initial microbial consortium that colonizes the basalt surface takes advantage of physical conditions in the porous grain interiors (Bagshaw et al., 2011) and catalyzes some of the most important mineral transformations including those of active Fe and Mn oxidation (Edwards et al., 2003; Bailey et al., 2009). Furthermore, the strong bonding that occurs between neo-formed inorganic colloids and microbial macromolecules, lipopolysaccharides, and nucleic acids, results in the long-term persistence of otherwise labile C forms in soil and sediment (Dontsova and Bigham, 2005; Omoike and Chorover, 2004, 2006; Mikutta et al., 2011). The formation of these secondary bioinorganic solid-phase products during pedogenesis in basalt has been shown to impact soil hydrology, with potential feedback to biogeochemical processing (Lohse and Dietrich, 2005). Additionally, there is strong evidence that organic compounds produced by bacteria and fungi influence soil structure, resulting in a more porous, ordered, and aggregated microenvironment (Feeney et al., 2006) with important consequences for water and gas retention and transport. Studying microbial community diversity on LEO hillslopes will thus be able to provide supporting insights into the biotic variable of landscape evolution.

In addition to studying microbial community diversity patterns on LEO, biogeochemical and hydrological weathering of basaltic soil material of LEO is of particular relevance to global carbon (C) and nitrogen (N) cycling. Despite making up only 5% of earth's land area, basalt silicates contribute to sequestration of atmospheric carbon dioxide (CO_2) over geologic timescales, accounting for 7% of total CO_2 uptake, and nearly 30% of the uptake associated with silicate weathering in particular (Gaillardet et al., 1999; Dessert et al., 2003; Suchet et al., 2003). In fact, initial experiments conducted in LEO indicated significant intake of CO_2 from atmosphere through weathering processes (van Haren et al.). The primary mineral assemblage of basalt weathers incongruently to form poorly crystalline secondary minerals (e.g., allophane, imogolite, ferrihydrite) of high specific surface area and chemical reactivity (Chadwick et al., 2003; Chorover et al., 2004; Dontsova et al., 2014), and these weathering products have been shown to form strong interbonded complexes with biogenic organic matter, thereby, stabilizing it against heterotrophic degradation over long timescales (Torn et al., 1997). The process of primary mineral weathering followed by translocation of released chemicals and secondary mineral formation contributes to nutrient stabilization in the system. As LEO evolves over time, one can anticipate critical opportunities for understanding the component roles of plants, soil food webs, biogeochemical cycle feedback, and a range of ecological processes shaping ecosystem development.

The LEO slopes have been designed to essentially track the evolution of a nascent landscape in the presence of carefully manipulated biological diversity, to understand and illustrate the subsequent coupling of biogeochemical Earth processes with the physical system. At LEO, we expect that biogeochemical "hot spots" will emerge reproducibly within the convergent hillslope structures, and that these "hot spots" will be loci of intense weathering, microbial growth, and plant establishment. Such locations will lead to the formation of nanoparticulate, bioinorganic weathering products (e.g., organometal and organo-mineral complexes) that will lead to (1) organic C stabilization against heterotrophic degradation and (2) hillslope-scale alterations in hydrological response of the hillslope. Our initial intent is to establish a suite of vascular plants that takes advantage of model systems sufficient to understand how diverse genotypes of the same species, or alternatively different species, may establish in the context of the heterogeneity of the LEO surface. Subsequent mapping of plant performance and the surface/subsurface characteristics that influence the ecophysiology of plant growth and reproduction will lead to a better understanding of how the factors that regulate the establishment of diverse plant communities, resource extraction dynamics, and the impacts of these plants on water/resource balance and soils. All of this is guided by an ecohydrological hypothesis of "homogenization" describing the effects of plants on surface water balance in the context of a variable environment (Ivanov et al., 2010). Over time, we expect to identify clear relationships between water movement, geochemical weathering, microbial diversity, and plant activity upon the hillslopes, thereby, enabling us to answer the bigger question of how landscape and life coevolve on our planet.

4.4 Conclusions

The LEO experiment, with all its instrumentation in place, is scheduled to start in 2016, when initially the evolution of the unvegetated landscapes will be observed under identical treatment regarding climate forcing. This initial phase is estimated to last for about 2–3 years, after which vascular plants will be introduced to the slopes in order to study how complex ecosystems alter the cycling of resources through these slopes and how they affect the evolutionary trajectory of the landscapes. This second phase is anticipated to last for another 6–7 years. Initial replication and identical experimental treatment of all three slopes will allow for significant model development that will allow for nuanced experimentation in the future, such as each replicate slopes being set on different climate trajectories, to observe how identical ecosystems are perturbed by different climate forcing. The data collected during this 10-year-long experiment and the knowledge gained from it will allow us to develop more powerful coupled system models that are capable of predicting landscape evolution in the real world in the context of climate change. Such tools are urgently needed to study the fate of ecosystem goods and services in the twenty-first century.

Many challenges remain, however, with any large-scale project like LEO. First, there are always design challenges along with logistical problems associated with a large-scale research infrastructure as LEO. These issues have been addressed thoroughly from a hydrological perspective in Hopp et al. (2009) and Dontsova et al. (2009) from a hydrogeochemical perspective, Ivanov et al. (2010) from an ecohydrological perspective, and Pangle et al. (2015) from an atmospheric perspective. The additional information about LEO observation capabilities given here are needed to convey the opportunities for coupled hydro–biogeochemical research.

With a team of diverse researchers, projects have to be planned out to best serve the interests of everyone without hampering the experimental requirements of any discipline or the future value of the infrastructure. Soil sampling on LEO is also a challenge since any activity that damages the soil material compromises the integrity of the hillslopes. To overcome these challenges, LEO researchers have put multiple strategies in place. All activities are planned and executed after considerable focus group meetings that address individual research concerns. A sampling strategy for microbial analyses that require destructive sampling is being developed to best capture the spatial heterogeneity of microbial communities without compromising the hillslopes. A crucial component of large-scale research infrastructures like LEO includes handling and archiving the entire data life cycle. The ability to store, access, analyze, share, and curate such vast amounts of big data, both pre- and post-publication are vital. With real-time data acquisition and archiving servers, and the presence of on-site analytical laboratories, LEO has the ability to manage the demands of multidisciplinary data handling. As a research infrastructure committed to model itself as a tool for the scientific community, collaborative research is highly encouraged for those keen on performing experiments at LEO or use its data sets. The biggest challenge, however, is to keep this research infrastructure running. While funds to build the infrastructure is one part, significant funding is also required to conduct research.

This chapter, together with Pangle et al. (2015), describes the research infrastructure available at the LEO at Biosphere 2, The University of Arizona, which is ambitious in its scope, capacity, and intent in serving as a community asset. This research infrastructure includes a dense network of automated sensors and samplers to observe water, carbon, and nutrient spatial and temporal dynamics in large-scale convergent landscapes comprised of ground basalt, as well as aboveground instrumentation for direct observation of water, carbon, and energy fluxes at the landscape surfaces. Moreover, sophisticated analytic instrumentation (dual laser spectrometers) allow for near real-time observation of the movement of water and carbon stable isotopes in the soil, atmosphere, and vegetation populating the hillslopes. The facility is unique in the world and provides opportunities to earth scientists, representing a wide range of disciplines (from hydrology to geochemistry to microbiology and ecology) to work in an interdisciplinary setting and address fundamental questions about the coevolution of hydrological, biogeochemical, and ecological processes and their interactions.

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