Biogeosciences survey: Studying interactions of the biosphere with the lithosphere, hydrosphere and atmosphere

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Progress in Physical Geography 2012 36: 833 originally published online 30 August 2012
DOI: 10.1177/0309133312457107

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What is This?
Biogeosciences survey: Studying interactions of the biosphere with the lithosphere, hydrosphere and atmosphere

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Abstract
The biogeosciences are a rapidly expanding field, and for this reason the full scope of possible topics falling under this heading is not always recognized. The biogeosciences cover all fields of the biological sciences and their interactions with the relevant Earth spheres (i.e. atmosphere, hydrosphere, lithosphere), and are studied over a wide range of temporal and spatial scales. While interdisciplinary work has been recognized for many years, it is recommended that all biogeosciences studies should ultimately strive to understand process operation and feedbacks, and in doing so a common ground to approaches of study can be defined. The notion of multidisciplinary versus interdisciplinary research is considered herein. It is by following an approach of explanation-based science that the complex interplay of biological and environmental processes can be understood best. Understanding of system behaviour and functioning should be a core goal of biogeosciences research. This review offers a proposed classification and summary of the full range of topics falling under the umbrella of the biogeosciences, and in doing so sets the stage for a future series of progress reports focusing on recent developments in the biogeosciences.

Keywords
biogeosciences, Earth spheres, ecology, geoscience, process

I Introduction and working definition
The biogeosciences cover all fields of the biological sciences and their interactions with the geosciences, and involve a large number of different processes, approaches and scales (Hedin et al., 2002; Nealon and Ghirose, 2001). By definition, the biogeosciences involve several interacting processes: living organisms rely on their environment, and in turn the environment is affected by these living organisms. This interdependence leads to a variety of complex feedbacks between the living and inanimate worlds that form the core of biogeosciences research.
Many of the subject areas in the biogeosciences cannot be dissected along traditional disciplinary lines without losing important aspects of process operation. The biogeosciences cover some of the most relevant and cutting-edge research themes within both the applied and theoretical natural sciences, ranging from topics such as geomicrobiology (e.g. Ehrlich and Newman, 2009; Konhauser, 2006; Loy et al., 2010), through to interactions between climate and living organisms (Ebi et al., 2009; McGregor, 2011; Tout, 1987) and even the possibility of life beyond our planet (Carr, 1996; Kasting, 1993; Staley, 2003; Wetherill, 1996).

The importance of interdisciplinary work has been recognized for many years, but what is most novel about recent developments in biogeosciences is an increasing emphasis on considering all research disciplines included within a project in a process-driven manner (Kearney and Porter, 2009; Martin and Bertazzon, 2010). In the past, it was often the case that one discipline treated phenomena associated with the other discipline as a static entity or a simple boundary condition. However, studies in the biogeosciences strive to move beyond these approaches and unravel the complex interplay of biological and environmental processes. To achieve the latter, such studies require the expertise of researchers from a variety of fields; this helps to ensure that each component of the interconnected system is considered appropriately (Hannah et al., 2004). A great challenge is for researchers to develop insights regarding approaches to address these complex linkages. If research is carried out by teams consisting of both biologists and geoscientists, then this allows the living and inanimate phenomena to be dealt with in a deeper manner, and promotes representation of the latest developments from the various disciplines. In the past, our understanding of individual processes and their complex interactions was often limited due to theoretical limitations in knowledge, lack of field methodologies and/or instruments at the correct scales, and/or lack of numerical modeling techniques for addressing system operation. Progress in both theory and methods has opened the doors to the development of advanced models of process and system operation.

For the biogeosciences to flourish and reach their full potential, Hedin et al. (2002), in their US National Science Foundation review, highlight the need to address existing limitations to interdisciplinary biogeosciences research that are created by institutional, programmatic and social barriers. Progress has been made to begin addressing these barriers over the past decade; for example, government funding agencies, such as the Canadian Natural Sciences and Engineering Research Council (NSERC), are beginning to adopt appropriate schemata for the review of interdisciplinary research proposals, while many universities now promote biogeosciences research clusters (for example, the Biogeoscience Institute, University of Calgary, with which the two authors of this review paper are associated). Many scientific organizations, such as the American Geophysical Union, now have distinct sections for the Biogeosciences that form the basis for conference sessions on this theme. Numbers of abstract submissions to the Biogeosciences Section at the Fall Meeting of the American Geophysical Union have increased markedly in the past decade (361 abstracts in 1999 to 1670 abstracts in 2011, AGU personal communication), demonstrating the growth in this research area. Conference sessions focusing on recognized disciplines within the biogeosciences have been growing in frequency (one example is the session on ecology/geomorphology interactions that has been held for the past several years at the Annual Meeting of the European Geosciences Union). Finally, new journals have been created that focus on either the biogeosciences in general or on specific subdisciplines (for example, the Wiley journal Ecohydrology).

Despite the great diversity of topics falling under the umbrella of the biogeosciences,
ranging from ecohydrology (e.g. Baird and Wilby, 1999; Eagleson, 2002; Wood et al., 2007) through to global biogeochemical cycles (e.g. Bashkin, 2002; Butcher et al., 1992; Schlesinger, 1997) (see also Table 1 for a more complete listing of subfields of the biogeosciences), the underlying foundation of biogeosciences research can be focused around several core themes. These themes are similar to those proposed by Hannah et al. (2004) in their working definition for ecohydrology; however, their ideas have been expanded below to consider any subfield falling under the banner of the biogeosciences.

1. The biogeosciences should include the full range of possible biological/ecological phenomena and their environments (e.g. lithosphere, hydrosphere, atmosphere). For example, plant responses are often a focus of many biogeosciences studies, but a complete definition of the biogeosciences must also include fauna (e.g. Porter et al., 2010). Terrestrial, river, lake, and marine environments, and even planetary studies (e.g. Osterkamp and Friedman, 1997; Rees, 2005; Rodriguez-Iturbe, 2000; Staley, 2003), fall under the umbrella of biogeosciences research.

2. Interdisciplinary research is fundamental to biogeosciences research, yet not all interdisciplinary research is undertaken in the same manner. Distinction can be made between multidisciplinary research and interdisciplinary research, with the former spanning across fields without necessarily tackling complex processes and coupling behaviours in all directions (Hannah et al., 2004). Hannah et al. (2004) go on to state that most published research in ecohydrology is completed by either teams of biologists or teams of Earth scientists; much fewer examples of studies could be identified in which the author list consisted of names of researchers from both disciplines. They observed that when one discipline dominates the research team, the second (and often just as important for system operation) discipline is not represented by experts in that field. In such cases, the necessary theory from the second discipline may not always draw from innovative aspects of that research area (see, for example, the discussion in Lancaster and Downes, 2010). Hannah et al. (2004) express concern that if researchers from the full range of disciplines do not participate in a study, then, for example, hydrologists tackling the ecological components in their work may reinvent the ecological wheel, and vice versa. The greatest possibility of providing a platform for novel points of departure lies in interdisciplinary work that considers system coupling and feedbacks.

3. To address the complex questions being asked by biogeosciences researchers, the focus and goals should be placed on processes, mechanisms and explanations operating over a full range of possible and appropriate scales (i.e. Kearney and Porter, 2009). A process-based approach is preferred over approaches that do not move beyond what may amount to largely empirical correlations between ecological and environmental variables. That being said, the latter type of research may have a role in elucidating spatial and temporal patterns that result from process operation and/or may provide important data and guide ideas at certain stages of research for a particular topic. The relevant processes and mechanisms are often very complex and may require the expertise of researchers from all relevant disciplines of the biogeosciences (see (2) above). Processes may involve complex non-linear and coupling behaviours that are often central to biogeosciences research (e.g. Jenerette et al., 2012; Pérez-Mercader, 2002; Stal- lins, 2006).
<table>
<thead>
<tr>
<th>Branch</th>
<th>Most Relevant Spheres</th>
<th>Comments</th>
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<tbody>
<tr>
<td><strong>BIOGEOPHYSICS</strong> dominant (some biogeochemistry may be involved)</td>
<td></td>
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<tr>
<td>Ecohydrology b Ecohydraulics</td>
<td>Biosphere, Hydrosphere Secondary: Lithosphere Atmosphere</td>
<td>• Interactions between microorganisms/plants/animals and components of hydrological cycle</td>
</tr>
<tr>
<td>Biogeomorphology b (sometimes called Ecogeomorphology)</td>
<td>Biosphere, Lithosphere Secondary: Hydrosphere, Atmosphere</td>
<td>• Interactions between microorganisms/plants/animals and geomorphological forms &amp; processes</td>
</tr>
<tr>
<td>Biometeorology Bioclimatology</td>
<td>Biosphere, Atmosphere Secondary: Lithosphere, Hydrosphere</td>
<td>• Interactions between biosphere and atmosphere; main difference is biometeorology involves time scales of order seasons or shorter, while bioclimatology involves time scales of order seasons or longer</td>
</tr>
<tr>
<td>Biophysical ecology</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• Interactions between plants/animals and physical environment; may consider individuals and/or groups and physiological and/or behavioural responses</td>
</tr>
<tr>
<td><strong>BIOGEOCHEMISTRY</strong> dominant (some biogeophysics may be involved)</td>
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<tr>
<td>Elemental cycles</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• May consider entire elemental cycle or aspects, such as: weathering, soil formation, biomineralization, rock forming processes</td>
</tr>
<tr>
<td>Geomicrobiology (important in Palaeobiology, Astrobiology and Bio-Oceanography)</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• Role of microbe and microbial processes in geological and geochemical processes and vice-versa</td>
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<tr>
<td><strong>COMBINED BIOGEOPHYSICS AND BIOGEOCHEMISTRY</strong></td>
<td></td>
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<tr>
<td>Ecopedology (Edaphology)</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• Interactions between biology and soil/regolith</td>
</tr>
<tr>
<td>Bio-oceanography</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• Considers biological components of oceans (marine organisms and ecosystems) in relation to physical and chemical aspects of oceans</td>
</tr>
<tr>
<td>Palaeobiology Palaeoecology</td>
<td>Biosphere, Lithosphere, Hydrosphere, Atmosphere</td>
<td>• This grouping is defined on the basis of a unifying temporal scale (as per descriptor palaeo); often, the stratigraphic record provides means to date and unravel past environments</td>
</tr>
<tr>
<td>Astrobiology</td>
<td>Spheres of other planets (comparisons made to Earth)</td>
<td>• Origin, evolution, distribution, and future of life in Universe; search for evidence of prebiotic chemistry, research into origins and early evolution of life on Earth</td>
</tr>
</tbody>
</table>

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a Some disciplines use the terms “eco” or “ecology” as part of the descriptor, while other disciplines use the terms “bio” or “biology”. In such cases, we have attempted to follow what appears to be main convention in the literature for that discipline. In addition, some disciplines may place two relevant sub-disciplines in a particular order; for example ecohydrology vs. hydroecology. There may be significance in that the first term is seen as a descriptor for the primary second term. We have attempted to follow what appears to be the primary convention for that discipline, but for simplicity, we have not included all possibilities.  

b To simplify our categorization, we have not included names of disciplines that have several sub-disciplines in their terminology, such as eco-hydrogeomorphology or eco-hydropedology. The classification quickly becomes cumbersome if all possibilities are included. However, the reader should be aware that such terms do exist in the research literature.
This broad survey of the field of biogeosciences sets the stage for a series of future invited progress reports that will explore recent developments in the biogeosciences. We want to emphasize that this initial review does not attempt to provide an exhaustive evaluation of all aspects and details regarding the numerous disciplines falling under the banner of biogeosciences research; such an undertaking is beyond the scope of this paper. Therefore, we limit this review on the biogeosciences to two primary goals: (1) to explain the significance of an interdisciplinary, process-based approach to biogeosciences research and the importance of developing integrated models and common ground in approaches; and (2) to define the full range of topics falling under the umbrella of the biogeosciences and provide a possible order and structure to biogeosciences research. We believe that the latter objective is particularly important to this initial review paper for the following reasons. Most researchers focus on only a few specific topics falling under the very broad category of the biogeosciences. Therefore, researchers are not necessarily aware of the full range of topics, many of which may not be closely related to their own area of expertise. Furthermore, existing reviews on the biogeosciences often miss certain disciplines in their definitions. For this reason, many of us by default have limited exposure and views about the entire scope of the biogeosciences.

II Why a ‘process-driven’ focus for biogeosciences?

Studies vary significantly in how they approach consideration of a scientific phenomenon. For example, some studies focus on correlations of system properties, which for biogeosciences research might involve making empirical associations between the relevant biological and environmental variables (see discussions in Kearney and Porter, 2009; Martin and Bertazzon, 2010). On the other hand, some studies may focus on process operation, mechanisms and feedbacks in an attempt to understand internal system functioning. We now discuss both of these approaches in relation to biogeosciences research, and the kinds of information that each can provide.

Empirical studies are often adopted in both the social and natural sciences due to their relative simplicity, and they can provide useful summary information for processes and systems about which relatively little is known. They can also provide information about spatial and temporal patterns in data that aids in the development and testing of process-driven approaches to explanation, such as numerical modelling. However, empirical studies by themselves lack explanatory power and focus on correlations between system variables (Kearney and Porter, 2009; Martin and Bertazzon, 2010). Complex process operation and feedbacks are often essential elements in system operation for topics falling under the biogeosciences. Since empirical approaches cannot provide information about complex internal system functioning, they should not necessarily be viewed as an endpoint for biogeosciences research. Furthermore, empirical correlations are specific to certain study locations and most often involve the requirement that external variables (e.g. climate, geology) remain stationary for results to hold true. For these reasons, empirical approaches may be most suitable at certain stages of biogeosciences research, such as to provide initial insights about a research topic, or to provide supporting ideas or test data for more explanatory, process-based studies and models.

Understanding of system behaviour and functioning should be a core goal of biogeosciences research. Process-based studies are explanatory in nature, and emphasize system functioning by investigating governing principles and processes; in other words, such approaches focus on how something operates, rather than inferring process operation based
on broad correlations as might be made in more empirically-based studies. Process-based studies may assume an underlying premise of direct cause-and-effect (determinism) while other studies may incorporate significant random elements, or some combination thereof (e.g. D’Odorico et al., 2006; Millán et al., 2010). Even if it is believed that a phenomenon is inherently deterministic, it is often the case that random elements must be included to account for the part of the problem that cannot be defined deterministically (Smart, 1979). Carrying on with this theme, Church (1996) describes how scale affects the manner in which we tackle processes for various phenomena, including how and when we might incorporate determinism and/or randomness within system explanation. Even though process-driven explanation may be the desired goal, studies may often incorporate probabilistic components within their explanations due to current limitations in knowledge or for practical reasons (Vogel, 1999). Process-driven models can be used to guide both field and laboratory investigations so that an improved understanding of probabilistic components can be obtained.

The development of process-based numerical models is critical to understanding system behaviour. Evaluation of model performance allows us to assess how well the processes and feedbacks are understood. The adoption of a process-driven approach for biogeosciences studies ensures that understanding and explanations are sought for the interdisciplinary questions being addressed.

III Which fields fall under the biogeosciences?

The term geobiology (e.g. Noffke, 2005; Thiel et al., 2011; see also the journal of this name) is sometimes used to refer to a collection of interdisciplinary research topics similar to those falling under the biogeosciences. However, topics in geobiology books and journals tend to have a particular focus on the evolution of life versus the broader scope of the definition of the biogeosciences adopted herein. It is important to note that there are branches of the biogeosciences (e.g. astrobiology) that consider life outside Earth (we will return to this later), but, unless specifically mentioned otherwise, the planet Earth is referred to in the following discussion.

The biological component of the biogeosciences covers the broad spectrum of topics falling under the biological sciences. The term biosphere is used to refer to all of the living organisms on Earth; that is, the microorganisms, plants and animals. Biological science considers these living organisms, including individuals and populations, and their evolution. Ecology is a particularly relevant subfield of biology for biogeoscience, as the study of ecology is concerned with the distribution and abundance of living organisms and how they interact with other organisms and their physical environment.

The term geoscience refers to any science that is concerned with the Earth and its three main spheres: the lithosphere, hydrosphere and atmosphere. The lithosphere refers to the solid outer layer of the Earth that is largely inorganic and covers the entire planet. While solid rock may be considered in biogeosciences research, the weathered upper layer of the lithosphere (i.e. regolith and/or soil) is particularly important for both plants and animals. The hydro- sphere contains the solid, liquid and gaseous water on the planet. It extends from some depth below the Earth’s surface to upwards of greater than 10 km into the atmosphere. Frozen water is often categorized under the separate heading of the cryosphere, but for this review it will be considered as part of the hydrosphere. The atmosphere refers to the gaseous particles that surround the Earth’s surface. There is no one definable boundary for the upper atmosphere, but it can be considered to be at an order of magnitude of 10^7 km above the surface of the Earth.
The biogeosciences involve the interdisciplinary study of topics that span the biosphere and any aspect(s) of the spheres associated with the geosciences (lithosphere and/or hydrosphere and/or atmosphere). Given the broad collection of topics falling under the umbrella of the biogeosciences, it is not surprising that a wide range of spatial and temporal scales are possible. Processes may be considered at spatial scales from the microscale (e.g. microbiology) through to regional and planetary scales (e.g. climate change and its biological interactions). Temporal scales may range from very short timescales (almost instantaneous) to many millions of years.

Table 1 provides one possible categorization for research disciplines falling under the umbrella of the biogeosciences; the reader should refer to this table as necessary throughout the following discussion. In our classification, we first provide three major groupings based on the extent to which biogeophysics, biogeochemistry or a combination of both provide the primary foundation for research topics falling under that category. Within each of these major categories, we provide a list of notable interdisciplinary fields falling under that designation. One could of course imagine other classifications. References given in the discussion that follows are examples and are not intended to be comprehensive.

I Ecohydrology

Ecohydrology considers interactions between hydrological and ecological processes for terrestrial landscapes, rivers and their floodplains (e.g. Brooks and Vivoni, 2008; Rodriguez-Iturbe, 2000). Integration between the traditionally defined fields of hydrology and ecology allows for progress in interdisciplinary studies focusing on both pure and applied science and water resource management. Fauna are sometimes overlooked in definitions and discussions of ecohydrology, although it should be considered a possible theme in ecohydrology.

Topics in ecohydrology have a relatively long history, with some particularly important work on plant/water interactions appearing during the mid-20th century in papers by Hack and Goodlett (1960) and Penman (1963). The adoption of the now commonly used term ecohydrology occurred in more recent decades (Hannah et al., 2004), with numerous textbooks and research publications appearing during this time period. The new Wiley journal Ecohydrology was initiated in 2008, signifying an important milestone in the history of the discipline. Bond (2003) noted that hydrologists have accepted and widely use the term ‘ecohydrology’, whereas biologists studying similar research topics seem to use the term less often. Hannah et al. (2004) believe that much ecohydrological research operates in a multidisciplinary mode rather than in a fully integrative interdisciplinary mode which, for reasons discussed earlier, may limit the possibility for innovative advancements in the field.

Present research focuses on a range of hydrological and ecological processes underlying climate/soil/vegetation patterns and dynamics. In particular, the topics of biodiversity and ecosystem functioning, which are so critical to ecosystem management and society, are explicitly addressed in ecohydrological studies. The volume titled Hydroecology and Ecohydrology edited by Wood et al. (2007) deliberately sets out to provide a more complete coverage of topics than previous books, including consideration of: ‘(i) a range of organisms (plants, invertebrates and fish’, (ii) physical processes within terrestrial, riparian (aquatic-terrestrial ecotones) and aquatic habitats, and (iii) palaeo-ecological/hydrological perspectives’ (Wood et al., 2007: xxiv). Chapters covered in this edited volume range from the ecohydrology of invertebrates associated with exposed river sediments (Sadler and Bates, 2007), flow-generated disturbances and ecological responses (Lake, 2007) and the
role of floodplains in mitigating nitrogen pollution (Burt et al., 2007) to hydroecology of alpine river systems (Brown et al., 2007).

Ecohydraulics is the name given to the particular branch of ecohydrology that considers interactions between ecology and the mechanics of flowing water. A recent review paper by Lancaster and Downes (2010) expressed concern that the ecological principles invoked in some ecohydraulic investigations are simplistic relative to current ecological understanding, a viewpoint that has led to further debate (Lamouroux et al., 2010). These concerns relate to point (2) in our working definition of biogeosciences and as also outlined by Hannah et al. (2004) in their review of ecohydrological research.

2 Biogeomorphology

The term biogeomorphology is used to describe the field of study that examines interactions between geomorphology and living organisms. Geomorphological processes and form impact living organisms, while living organisms, in turn, influence geomorphology.

While examples of studies integrating geomorphology and ecology date back over 100 years, it was only in the 1980s and 1990s that the term biogeomorphology began to appear in mainstream use, with examples being a book by Viles (1988) and an emphasis in sessions at various conference venues (Wheaton et al., 2011). It was during this time that feedbacks between geomorphology and ecology began to be investigated, rather than vegetation being treated as a relatively simple boundary condition for geomorphological phenomena.

At intermediate to longer timescales, examples of topics that have been studied include interactions between riparian vegetation and stream channels (Charron et al., 2011; Rood et al., 1998; Scott et al., 1996) and more recently process interactions between vegetation and drainage basin form and development over longer timescales (e.g. Dietrich and Perron, 2006; Istanbulluoglu and Bras, 2005; Martin, 2007). Research at the micro-scale has generally received somewhat less attention, with examples of topics requiring further consideration including interactions between plant species and soil chemistry, soil hydrology, and soil erosion (Osterkamp and Friedman, 1997). The reader is referred to the 2009 Virtual Themed Issue of *Earth Surface Processes and Landforms* titled ‘Reappraising the Geomorphology – Ecology Link’ (edited by S. Darby), which provides examples of the current range of topics being considered in biogeomorphological research.

Phillips (1995) and Stallins (2006) have also made important contributions to biogeomorphology, respectively addressing the issues of scaling and complexity. Phillips emphasized discrepancies in temporal scale between geomorphological and ecological processes (see also De Boer, 1992; Huggett, 1991; Levin, 1992; O’Neill, 1989; Rosswall et al., 1988; Schumm, 1988), which presents an interesting challenge when constructing models of process operation. The concept of uni-directional versus bi-directional interactions between geomorphology and ecology was addressed by both Stallins (2006) and Wheaton et al. (2011). Stallins (2006) also utilized the framework of complexity theory to address bi-directional coupling of geomorphological and ecological processes.

3 Biometeorology/bioclimatology

Biometeorology and bioclimatology consider interactions between the atmosphere, including weather, climate, electromagnetic radiation and pollutants, and humans, animals and plants (including domesticated species and agricultural crops) (McGregor, 2011). Numerous aspects of weather and climate affect biological processes, including solar radiation, temperature and humidity; in turn, living organisms affect weather and climate. Biometeorology and bioclimatology have a particular focus on the processes that
govern mass and energy exchanges between biological phenomena and the atmosphere, with environmental physiology being a topic of central concern (Folk, 1997; Fregly and Blatteis, 1996).

While the origins of this discipline date back thousands of years, remarkable growth in this research area began in about the mid-20th century (Tout, 1987), with the publication of key books and edited volumes following thereafter (Folk, 1966; Gates, 1972; Landsberg, 1969; Lowry, 1968; Tromp, 1962). A monograph by Folk (no date) outlines the founding in 1956 of the International Society of Biometeorology (ISB), which represents a critical development in the history of the discipline; its founding demonstrates the recognition of biometeorology as a distinct topic of study and provided a focused structural organization for researchers. Burton et al. (2009) review the long tradition of biometeorology in the biophysical sciences, and also address the greater accountability in terms of perceived societal value that is increasingly an expectation of research in this discipline.

In recent years, a proliferation of research studies that are applied in nature has appeared, in addition to more theoretical work. There is a particular interest in studying the processes by which living organisms adjust to changing environmental conditions, such as climate change (e.g. Burton et al., 2009; Gaughan et al., 2009; Orlandini et al., 2009). Recent issues of the *International Journal of Biometeorology* display the wide range of topics covered by this discipline; for example, in a recent issue of this journal, topics ranged from estimates of energy fluxes in a semi-deciduous forest (Sanches et al., 2011) to the influence of atmospheric states in semi-arid regions on mental disorders (Yackerson et al., 2011).

4 Biophysical ecology

Spotila and O’Connor (1992) provided an introduction to the field of biophysical ecology in a special issue of the journal *American Zoologist*; this introduction provides the basis for a number of the themes covered in the following discussion. Biophysical ecology focuses on understanding the physics-based, mechanistic processes and conditions (e.g. climatic) that form the environment for plants and animals.

A growing interest in this discipline began in about the mid-20th century, which signified its development as a more unified research area. Overall, more effort has been put forth in the application of a biophysical approach to plants compared to animals, although biophysical approaches provide important mechanistic insights into issues surrounding animal competition, population dynamics, and behaviour (Spotila and O’Connor, 1992).

Current themes representing the cutting edge in biophysical ecology focus on heat and mass transfer variables required to explain survival, growth, reproduction and species distributions, with a particular emphasis on physiological and/or behavioural responses (the latter being relevant only to animals) (Campbell and Norman, 1998; Gates, 1980; Kearney and Porter, 2009; Porter and Gates, 1969). Porter and collaborators, in their body of work, emphasize the physiological factors that link ecological response with environmental conditions (e.g. Kearney and Porter, 2009; Porter et al., 2002, 2010). Kearney and Porter (2009) and others (e.g. Dormann, 2007; Pearson and Dawson, 2003) have expressed concern with correlative approaches often adopted to study interactions between plant/animal ecology and the environment. While developments in Geographic Information Systems (GIS) and remote sensing have allowed for much improved knowledge of climatic, terrain and other environmental factors important to biophysical ecology, many studies utilizing this information have not moved beyond non-explanatory empirical analysis (Kearney and Porter, 2009). As another example of this type of concern, Davis et al. (1998) discuss the limitations associated with a simplistic ‘climate envelope’ approach for how individual species respond to climate change; limitations
include lack of consideration of dispersal, species interactions and other population dynamics processes.

5 Elemental cycles (biogeochemistry)

At the broadest scale, elemental cycling is considered under the heading of global biogeochemical cycles, but elemental cycling can be investigated at all spatial and temporal scales (from microseconds to millions of years, from individual molecules to global scales). Elemental cycling considers interactions and feedbacks between the biology and chemistry of our planet by investigating the transformations, transport and storage of chemical elements through the various spheres of the Earth (i.e., biosphere, lithosphere, hydrosphere, atmosphere) as driven by solar energy and/or geothermal energy (e.g. Archer, 2010; Garrels and Lerman, 1984; Selin, 2009).

Biogeochemistry is among one of the more mature disciplines in the biogeosciences (Cutter, 2005); indicative of its maturity is the Kluwer journal of this name initiated over 20 years ago, and numerous textbooks on this topic that have appeared during this time. Cutter (2005) also emphasizes the large number of peer-reviewed articles appearing annually that contain the term ‘biogeochemistry’ in their title. However, Cutter goes on to state that a balanced approach to the biological, geological and chemical aspects of research questions is not often found in these papers (in other words, particular aspects are emphasized more than others). Cutter advocates a stronger focus on the interactions and feedbacks between various aspects of a problem and less on the individual components.

Critical feedbacks modulate the resulting environmental conditions and maintain conditions that are habitable for life on Earth (e.g. Berner, 1989; Watson and Lovelock, 1983). Elemental cycling and interactions between biology and the environment have been central to the evolution of Earth and life; for much of Earth’s history, the resultant changes produced by chemical reactions have proceeded at relatively slow rates, and biological life has had time to adapt during the course of evolution (Schlesinger, 1997). It is now well recognized that there are few natural chemical reactions on Earth that are not influenced by living organisms; the study of geochemistry of the Earth is almost invariably the study of biogeochemistry (Schlesinger, 1997). Over long timescales, life on our planet and interactions with the surrounding environment have contributed to the development of the atmosphere and hydrosphere (Van Cappellen, 2003). In modern times, human beings are profoundly modifying the biogeochemistry of the Earth. For this reason, past and modern-day studies, including those considering human-influenced and/or natural systems, are important components of biogeochemistry research (e.g. Berner, 1989; Cutter, 2005; Mackenzie et al., 2002; Miller, 1953; Peierls et al., 1991; Ronen et al., 1998).

6 Geomicrobiology

Geomicrobiology is a well-recognized subdiscipline in biogeosciences research that has undergone significant advances in the past several decades (e.g. Ehrlich and Newman, 2009; Konhauser, 2006; Loy et al., 2010). Geomicrobiology studies the role of microbes and microbial processes in affecting geological and other Earth processes, including those occurring in the crust and in water bodies (oceans, lakes, etc.) and how these, in turn, affect microbes. Although geomicrobiology plays a central role in astrobiology and is important in elemental cycling (two other research categories defined in this review paper) (e.g. Falkowski et al., 2008; DesMarais and Walter, 1999), it warrants its own category and discussion.

Ehrlich and Newman (2009), in the opening pages of their book on geomicrobiology, outline the history of geomicrobiological studies, and
we refer the reader to their discussion for more detailed information. Ehrlich and Newman (2009) state that it is not certain when the term geomicrobiology was first introduced, but they note that Beerstecher (1954) used this term to refer to the relationship between Earth history and microbial life while Kuznetsov et al. (1963) considered the study of current microbial processes and their role in both the solid Earth and water bodies. Some researchers in the 1800s (e.g. Ehrenberg, 1838) and early 1900s (e.g. Nadson, 1903, 1928) considered topics that would now be considered within the field of microbiology, but it was not until the 1980s that geomicrobiology began to be a focus of targeted attention. Among other achievements, early research identified the importance of certain microbes in transformations related to weathering and other Earth processes, and also began to emphasize the role of microbes in the origin and evolution of life on our planet (Ehrlich and Newman, 2009). Advances in how microbial life affects the Earth have been notable in the past several decades, including recognition of the great depth to which microbial life may be found within the Earth’s crust, and this in turn has influenced the field of astrobiology (Konhauser, 2006).

Microorganisms have existed on Earth since its early history, and their significant role in the development of Earth and its atmosphere are well recognized. Recent years have witnessed an even greater appreciation of the role of microbial processes in the multitudes of geochemical processes associated with our planet (Nealson and Ghiorse, 2001). Microbial life set the stage for the development of increasingly complex life forms, and in more recent decades scientists have begun to identify a much fuller range of environments in which they can exist, including what initially might be thought of as very inhospitable environments (e.g. Dong and Yu, 2007; Fredrickson and Balkwill, 2006; Ventosa, 2004; Wynn-Williams, 2000). Microorganisms are now known to be involved in large numbers of geochemical reactions, such as mineral breakdown and element transformation, which can have significant impacts on the surrounding environment, and the atmosphere in particular (Nealson and Ghiorse, 2001).

7 Soil ecology (ecopedology, edaphology)

Ecopedology considers soil ecology and the interactions between soils and terrestrial ecosystems (e.g. Lal, 1987; for other examples, see books by Bardgett, 2005; Coleman et al., 2004; Killham, 1994), often with a particular focus on plants. The term ecopedology (and the sometimes used term edaphology) is not widely used in the refereed scientific literature, nor does the term ecopedology appear in the relevant book titles for this discipline; the term soil ecology is generally used. In this discussion we will use the term soil ecology, given its more widespread occurrence in the literature. Soils originate from physical, chemical and biological interactions between the originating parent material and the atmosphere and hydrosphere. Some aspects of soil ecology may be considered in other branches of the biogeosciences (elemental cycling, biogeomorphology, ecohydrology), but it makes sense to include a category in our classification that has a particular focus on soil and ecological interactions.

Soil ecology has been a recognized field of study for a number of years (e.g. Lyon and Buckman, 1929). This research area considers how chemical, physical and mineralogical properties affect organisms and how they, in turn, affect soils. Lavelle and Spain (2001) state that the study of soil biology is not as advanced as the related disciplines of soil physics and soil chemistry, and that it also lags behind the study of above-ground biological systems. Some of this lack of progress was attributed to a predominantly uni-directional consideration of how organisms affect process and system functioning, rather than also considering how soil processes affect living organisms. Killham (1994) states that previous books about soil ecology tended to focus on microbes, plants or animals,
while in his book an attempt is made to integrate all of these phenomena.

Coleman et al. (2004) define living organisms as a component of soil, and interactions between the living and non-living components form the basis for the study of soil ecology. Moving beyond the soil itself, soil is a component of the terrestrial ecosystem, and thus is involved in a series of interrelated processes and feedbacks among animals, vegetation, the atmosphere, the hydrosphere and soil. There remain many questions concerning the processes that affect how organisms in soils are distributed, interact and live, and the role of biota in soil processes has not always been fully recognized (Paton et al., 1995). Paton et al. (1995) discuss the focus that had been placed previously on downward, vertical soil-forming processes and mature soil profiles. While the concept of bioturbation (soil mixing by biological agents) was recognized in the 19th century (Darwin, 1881; Shaler, 1891), it is only in more recent years that its significance to soil development has once again been more fully appreciated.

Societal issues such as the feeding of the world’s population (and the related issue of sustaining soil fertility) and climate change have given renewed relevance to the discipline of soil ecology (Lavelle and Spain, 2001). In addition, the adoption of newer techniques in molecular biology have allowed for recognition that soil organisms are not distributed in a homogeneous manner within soils; for example, ‘hot spots’ of soil biological productivity are increasingly being recognized (Coleman et al., 2004). Killham (1994) emphasizes that bulk measurements of soils, which are often applied within the context of many studies, do not reveal enough critical information about the spatial variability to unravel the complexity of process operation within soils.

8 Bio-oceanography

Bio-oceanography considers the interactions between marine life and ocean processes, and is a vital discipline within the broader field of oceanography (Rees, 2005). Living organisms considered in bio-oceanography include microbial life, fish and marine mammals. Depending on the living organisms being studied, the relevant oceanic processes may vary considerably, ranging from photosynthesis, nutrient and element cycling, ocean currents and seawater chemistry to ocean floor geologic processes (e.g. Cullen et al., 2002; Huntley et al., 1991; Smetacek et al., 2004).

The past several decades have witnessed the collaboration of marine biologists with both physical and chemical oceanographers to understand marine ecosystems, thus leading to maturation in the field of marine ecology (Mann and Lazier, 2006). Prior to this, learning (including formal university courses) tended to be divided into studies that were either primarily biological or physical in nature. A large increase in the number of publications in integrated oceanography at scales ranging from small to larger spatial and temporal scales occurred between 1991 and 1996 (Mann and Lazier, 2006). While early work recognized the key role of physical mechanisms in affecting marine populations, it is now recognized that organisms also affect coupled physical-biological processes (Mann and Lazier, 2006).

DeLong and Karl (2005) emphasize that while the foundations of physical and chemical processes in oceanography are relatively well understood, knowledge of oceanic microbial processes is in comparatively early stages of research and this presents a particularly exciting branch of bio-oceanography. This topic is now receiving a great deal of attention, and considers marine microbes and their connections to other biological and Earth systems (e.g. DeLong and Karl, 2005; Kolber, 2007; Rees, 2005) (see also the discussion on geomicrobiology earlier in this paper). Unlike terrestrial habitats, microorganisms are the central type of biomass in oceans (Giovannoni and Sting, 2005; Kohfeld et al., 2005). As pointed out by Rees (2005) in
her introduction to an ‘Insight’ in Nature, it is now recognized that marine microbes are accountable for roughly half of the primary productivity of our planet, and that they are critical regulators of biogeochemical processes involved in elemental cycling. Observations of microbial and other oceanic processes are now being connected and integrated into our understanding and explanation of other phenomena, such as the atmosphere and marine and/or terrestrial ecosystem functioning at various levels (Arrigo, 2005; DeLong, 2007; Huntley et al., 1991; Kohfeld et al., 2005; Smetacek and Nicol, 2005).

9 Palaeobiology/palaeoecology

Palaeobiology and palaeoecology in the biogeo-sciences context include reconstruction of the history of Earth and the joint interactions between life and Earth’s environment, with the interactions being bi-directional in nature (Knoll, 2003; Noffke, 2005). A particular focus is placed on the origin and evolution of the biosphere and its connections to changing Earth environmental conditions over time (Brenchley and Harper, 1998). A common factor that unifies studies falling under this category is a focus on the prehistoric time period, necessarily implied by the term ‘palaeo’. These kinds of studies may focus on any of the possible environments associated with Earth’s spheres as discussed in the previous categories above (hydrology, geomorphology, soils, atmosphere, oceans, etc.). For this reason, palaeobiology and palaeoecology can also be viewed as natural extensions of any of the earlier-defined categories, with the difference being that the time period of consideration is prehistoric. Environments in existence throughout Earth’s history are often very different from the more familiar environments of the modern age, and evidence (found, for example, in the fossil record of old rocks) is used to infer past environmental conditions (Brenchley and Harper, 1998). In addition to evidence found in rock and sedimentary records, the use of other approaches, such as employing suitable proxies and numerical modelling, may also provide evidence for these kinds of investigations. Unfortunately, rock and other records are often incomplete, which means that evidence may be missing for particular periods of time.

Because palaeoecology focuses on past ecology based on fossil evidence, it developed its own distinct methodologies and to some extent has been treated as a separate discipline from ecology, often being referred to as palaeontology (Rull, 2010). Researchers studying palaeoecology come from diverse backgrounds, such as biology, geology, anthropology and climatology. In the past, many studies falling under the category of palaeobiology or palaeoecology were largely descriptive, whereas recent years have seen an increase in studies with a more process-based focus. Nonetheless, key theoretical developments in modern ecological studies have not always been incorporated into palaeo-studies. Recent years have witnessed attempts to bridge these gaps, and improved synergy has resulted. Reflecting on these developments, Davis (1994) urged palaeoecologists to place a particular focus on hypothesis testing and improved data quality, rather than emphasizing descriptive interpretations. Rull (2010) believes that these objectives are currently being met. In addition to modern ecology lending theoretical insights to palaeoecology, it must be recognized that palaeoecology has an important role in improving our understanding of medium to long-term ecological/environmental process operation and interactions.

Process-based studies in palaeoecology have been important in revealing that some widely believed ideas in Pleistocene ecology and geoscience are not necessarily correct. For example, Davis and Shaw (2001) found that most plants and animals migrated into new habitats throughout the interglacial. One implication is that interglacial periods may not be long enough for plants and animals to cover the complete range that they otherwise might cover (i.e.
the flora and fauna are not in equilibrium with the environment. Ecosystems throughout the interglacial are also subject to invasion by new species. Modern species evolved in the Pleistocene, during which abiotic and biotic instability was the norm. Good examples of a process-based approach to palaeo-studies in the biogeosciences are those associated with past climate change (Hansen and Sato, 2012).

10 Astrobiology

The field of astrobiology focuses on the origins and distribution of life in the Universe (Staley, 2003), and by definition considers many branches of the physical and biological sciences. This is a unique category as it considers the earliest time periods in the Earth’s history (e.g. Bada et al., 1994; Kasting et al., 1993; Schopf, 1983), and it also focuses on life outside Earth in the rest of the Universe (with a large focus on the planet Mars) (Bell, 1996; Boston et al., 1992; Carr, 1996; Clark, 1998) and further afield (e.g. Kasting, 1997; Kasting et al., 1993; Leger et al., 1993; Wetherill, 1996).

Astrobiology differs from exobiology, with the latter focusing only on life outside Earth, whereas astrobiology also includes the study of life on Earth. For many decades, NASA sponsored a programme in exobiology, a topic that refers to the study of life outside Earth (Staley, 2003). However, the term astrobiology was eventually adopted by NASA, and it considers life on and outside Earth. This concept has become generally preferred to exobiology. It is now realized that studies on Earth provide critical clues about life in the rest of the Universe, and vice versa (e.g. Jakosky and Skock, 1998; Nealson, 1997). Cumulative advances in knowledge from contributing fields such as microbiology, astronomy, geochemistry and palaeontology have allowed for the development of the field of astrobiology (Staley, 2003).

In its consideration of life on Earth, astrobiology focuses on the dating of early events and life on Earth that provide clues to the origins of life both on our planet and in the Universe (Staley, 2003). New methods of molecular analyses and approaches to recognize the signatures of life have allowed for remarkable advances in the study of microbial life and the range of environments in which it can exist (DesMarais and Walter, 1999). It has been found that microbial life can tolerate particularly extreme conditions, and this provides clues for astrobiologists interested in the possible habitable environments for life that may exist during planetary development (DesMarais and Walter, 1999; Dong and Yu, 2007; Fredrickson and Balkwill, 2006; Ventosa, 2004; Wynn-Williams, 2000). As our understanding of what constitutes the full range of habitable conditions for life on Earth increases, the range of possible environments for life to develop in the rest of the Universe likewise increases. Furthermore, power-law scaling and its connection to critical states in astrobiology may help shed light on the conditions necessary for the emergence of extraterrestrial life, as well as life on Earth (Perez-Mercader, 2002).

IV Concluding thoughts

This review has demonstrated the wide range of topics falling under the banner of the biogeosciences; we believe that Table 1 represents one of the most complete listings of topics in this discipline that has been published to date. This survey of the disciplines within the biogeosciences, with information that includes for each discipline its scope, history and current research themes, demonstrates the breadth of the field of biogeosciences, as well as the commonalities in approaches and methods of various components of the field. In doing so, we hope to promote dialogue and integration between the various disciplines, as well as to set the stage for our future, more focused, progress reports.

Other themes pertinent to all disciplines within the biogeosciences have been discussed,
including the importance of interdisciplinary, process-driven research, which we believe is necessary for innovative progress to occur. This is best accomplished by ensuring whenever possible that specialists from all relevant disciplines are involved in research projects. The inclusion of a full range of experts allows for the greatest possibility of innovative advancements in our understanding of process operation, including the often complex feedbacks and connections between living organisms and various aspects of their environment. The discussions of each of the 10 disciplines identified in this review show that researchers are increasingly recognizing the need for collaborative, interdisciplinary research. Such collaborations have led to innovative and outstanding progress in many research areas, with geomicrobiology and astrobiology being particularly good examples. Furthermore, advances in computing technology, experimental/field instrumentation and dating techniques have allowed for notable progress in the development of process-based models and the acquisition of field data to support these models. Knowledge about particular processes can be applied within unifying numerical models of system operation for the particular system being studied. When applied to interdisciplinary research projects, advanced models allow for investigation of the complex interplay and feedbacks between biological phenomena and environmental conditions.

The integrative type of science outlined in this review is very relevant to land managers concerned with environmental policy, and to society. Traditional discipline-specific science has difficulties addressing many of the problems facing society because individual disciplines do not generally concern themselves with detailed understanding of the full range of processes and feedbacks found in biogeochemical systems. Biogeochemicals research is now undergoing a phase of great discovery and rapid progress, in large part due to our increased understanding of process operation for the full spectrum of topics being studied.

Acknowledgements
We gratefully acknowledge the support for our biogeochemistry research initiative provided to us by our association with the Biogeochemistry Institute, University of Calgary. NSERC Discovery Grants awarded to Edward Johnson and Yvonne Martin have allowed us the opportunity to explore biogeochemistry questions. We thank the numerous undergraduate and graduate students who have provided biogeochemistry research insights and assistance over the years. We also thank the four anonymous reviewers for their perceptive comments that helped to strengthen the manuscript.

Funding
This work was supported by the NSERC Discovery Grants of Yvonne Martin and Edward Johnson.

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