Chapter One
Geomorphology and the Terrestrial Carbon Cycle

> The terrestrial carbon cycle is currently the least constrained component of the global carbon budget.
>
> (Bloom et al. 2016: 1285)

Introduction

As global atmospheric carbon concentrations continue to rise, there has been an increasing focus in the twenty-first century on understanding terrestrial components of the carbon cycle. This has been a major interdisciplinary research agenda and advances in remote sensing and modelling of vegetation systems have developed increasingly detailed understanding of above ground carbon cycling (Fatichi et al. 2019; Lees et al. 2018). Similarly, the storage of carbon in soils below ground has been the focus of extensive and detailed research (Wiesmeier et al. 2019). However, arguably, understanding of soil carbon processes lags behind analysis of above ground systems. For example, it is notable that in the paper cited at the top of this chapter (Bloom et al. 2016), the terrestrial carbon model that the paper considers includes significant detail around the cycling of carbon through biomass, modelling carbon in leaves, roots and wood separately, whilst soil carbon represents a single store.

Where more detailed models of soil carbon cycling are applied that consider multiple solid carbon pools (e.g., Abramoff et al. 2018), a notable absence is consideration of lateral transfers of organic carbon in the soil and sediment

Geomorphology and the Carbon Cycle, First Edition. Martin Evans.

system. Over the last ten years however, there has been an increasing recognition of the importance of lateral carbon fluxes within the landscape as a key part of understanding carbon dynamics at the large scale (e.g., Battin et al. 2008). Figure 1.1 is the 5th Intergovernmental Panel on Climate Change (IPCC) representation of the terrestrial carbon cycle (Cubasch et al. 2013). Flux from the land to the oceans is represented by the fluvial carbon flux. Whilst the IPCC estimates distinguish pre-industrial and post-industrial fluxes for many of the key elements of the cycle, human impacts are not quantified for the fluvial system. Clearly a more detailed picture of the fluvial system is required. The fluvial

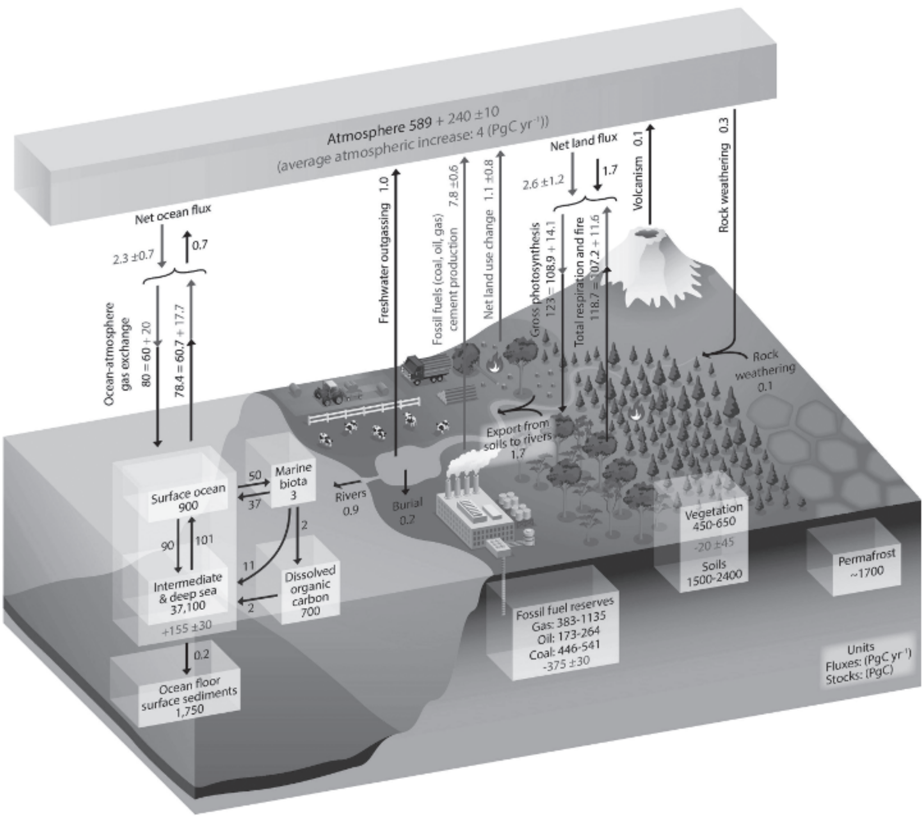

Figure 1.1 A simplified schematic of the global carbon cycle. Black text indicates pre-industrial stores and fluxes and grey indicates estimated changes post circa 1750. Source: After Ciais et al. 2013. Figure 6.1 in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 471). Reproduced with permission of Cambridge University Press. (https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf)

carbon flux is relatively small compared to the magnitude of terrestrial carbon storage, but is simply the residual of carbon transformation which occurs as organic matter is transported from headwaters to the oceanic sink. Much of the uncertainty about the relative importance of lateral carbon fluxes in the terrestrial carbon budget stems from a lack of knowledge about how large this residual is as a proportion of the total amount of organic carbon which is transported and delivered from hillslopes.

Organic carbon in solid or particulate form is transported from hillslopes to the fluvial system, and can be transformed or mineralised in transit either physically, or through the action of macro and micro biota. Transit of organic matter across hillslope systems is however complex and variable in time and space. The proportion of organic sediment eroded in a given period or event that is delivered to the river system (the sediment delivery ratio Walling 1983) is considerably less than 100%, so that an understanding of hillslope geomorphology is required to determine where eroded carbon is deposited. Once organic matter reaches the river system, timescales for direct transfer of dissolved and suspended material to the ocean are typically hours to days (e.g., Jobson 2001). However, Ferguson (1981) described the fluvial sediment transport as a 'jerky conveyor belt' so that a proportion of sediment is redeposited within the fluvial system (on bars or floodplains, or in lakes or reservoirs). Material may be mobilised and redeposited multiple times before reaching the ocean, so that virtual velocities may drop by several orders of magnitude and travel times are consequently measured in centuries rather than days. The transit of organic carbon from hillslope source (involving the processes of carbon fixation by vegetation and transfer of litter to the soil system) to oceanic sink is complex. Along the way, material may be stored in zones of sediment accumulation (depositional landforms), representing long-term carbon sequestration or alternatively may be mineralised and lost to the atmosphere through processes of microbial decomposition and respiration. The interactions of carbon fixed by the terrestrial biosphere within the sedimentary system are significantly more complex than the representation in the IPCC carbon budget.

Initially work on lateral transfers of carbon tended to be focussed on the transformation of organic carbon within freshwater systems, building on concepts such as the River Continuum Concept (Vannote et al. 1980). This concept postulates predictable patterns of downstream change in organic matter quality as it is cycled by in-stream processes. Increasingly however, the role of geomorphological processes in controlling the lateral transfer of carbon on hillslopes and through river systems has been recognised (e.g., M. Evans et al. 2013; Hoffmann et al. 2013a). Agricultural hillslope systems have been a major focus of geomorphological work in this area and anthropogenic modification of these systems constitute a major alteration of the overall terrestrial carbon cycle. However, a focus on agricultural systems has tended to drive a focus on field scale patterns of sediment transfer.

Unpicking the black box of headwater to ocean carbon transfers implied in Figure 1.1 requires consideration of carbon fluxes across the entire sediment cascade. A rapidly expanding body of geomorphological research has begun to explore the role of the sediment system in the terrestrial carbon cycle (e.g., Hoffmann et al. 2009; Kirkels et al. 2014). However, the focus of geomorphological carbon cycling research has predominantly been on characterising the magnitude of carbon storage in major loci of sediment accumulation (depositional landforms). There is increasing recognition that a complete understanding of sedimentary carbon storage also requires analysis of rates of carbon addition and removal from storage, and the processes which control this. This requires an integration of biological and geomorphological analyses. Nevertheless, despite the call by Slaymaker and Spencer (1998) for biogeochemical cycling to become a central concern of physical geography and geomorphology, the wider engagement of geomorphology with an understanding of biogeochemical cycling has been so far limited.

In the context of a rapidly shortening time horizon for effective action to mitigate rising greenhouse gas concentrations in the atmosphere, it is argued that rapid progress in this area is vital. The requirement to deliver a more complete understanding of the terrestrial carbon cycle has two main components. Firstly, a functional understanding of the processes which drive carbon flux through the terrestrial system is needed in order to understand the interaction of the terrestrial biosphere with excess atmospheric carbon derived from fossil fuel use. In particular, a focus on carbon storage and release in the terrestrial system is fundamental to identifying positive feedback mechanisms and threshold conditions that might exacerbate anthropogenically driven rates of change. Secondly, understanding the processes by which carbon is added to major terrestrial carbon stores, such as live biomass and particularly soil and sediment carbon storage, offers the potential to manipulate these natural systems to sequester carbon and therefore potentially provide some mitigation of rising atmospheric carbon levels.

Increasing amounts of academic labour are being focussed on these critical problems, but arguably too much of this work is siloed within traditional disciplinary structures and networks. This book is written from the perspective of a geomorphologist trained in geography departments in the UK and Canada, and is born partly from the conviction that there is much which traditional geomorphological understanding of landscape systems can bring to the grand challenge of understanding and managing terrestrial carbon storage. A multidisciplinary approach is fundamental to meeting this challenge; this book will both explore and explain the ways in which geomorphological understanding can contribute to, and also identify the challenges of integrating this knowledge, with understanding of the biosphere and its role in the fixation and release of atmospheric carbon.

The Aims of This Book

The overall aim of this book is to develop a research agenda for the integration of geomorphological, biological and microbiological understanding into analyses of the terrestrial organic carbon cycle. To achieve this, this book has three main objectives:

1) To identify challenges and opportunities in the application of geomorphological methods and insights to the analysis of terrestrial carbon cycling.
2) To synthesise the rapidly expanding understanding of geomorphology and carbon cycling in the academic literature to define the state of the science.
3) To develop a conceptual framework based on geomorphological theory, and informed by work in ecology, microbiology and biogeochemistry, in order to analyse spatial patterns of terrestrial carbon cycling at the landscape scale.

Achieving the aim of fully integrating geomorphological expertise into a multidisciplinary approach to the analysis of terrestrial carbon cycling will not happen just because this integration offers answers to key questions, it also requires an understanding across scientific communities of what those questions are. This book is written with three audiences in mind. It is written for geomorphologists, to provide a synthesis for those in the field, but also to persuade the wider geomorphological community that core geomorphological data, skills and understanding are required to untangle the complexities of the terrestrial carbon cycle, and that they hold the key to progress in this area.

This book is also written for biologists and microbiologists whose work drives our understanding of both the fixation of atmospheric carbon and the mineralisation of soil carbon, which underpins carbon sequestration into sedimentary stores. This book will make the case to this audience that the physical movement of carbon substrate across the landscape, and the disturbance of equilibrium communities that are associated with phases of erosion and deposition, are components of carbon cycling which need to be integrated into an understanding of carbon storage at longer timescales. These decadal and longer timescales are critical in the context of anthropogenically driven changes in atmospheric carbon concentrations over similar periods.

Finally, this book aims to engage with the community who manage the terrestrial system. Landowners, planners and policy makers are the people who have the capacity to effect change in the anthropogenically dominated landscape that we live in. Managing erosion through landscape restoration, re-naturalising river courses and modifying agricultural practices are all components of conservation practice which drive change in biological and geomorphological systems, and thus modify the flux of carbon through terrestrial systems. Understanding these changes offers the potential to design such interventions in ways which maximise carbon sequestration into sedimentary stores, and so have potential to mitigate some anthropogenic carbon emissions. By characterising these stores and the processes which control carbon sequestration at a range of timescales, this book will offer the potential to argue for carbon sequestration co-benefits in landscape conservation schemes.

Organisation and Focus of This Book

The main argument of this book is developed in three parts. **Part I** (Chapters 2–4 of this book) outlines the key elements of the fast (organic) and slow (inorganic) terrestrial carbon cycles (Chapters 2 and 3 respectively), in order to provide the context for the discussion of geomorphological influences on carbon cycling in the subsequent chapters. The main focus in this book is on the fast carbon cycle, but a review of the key elements of the slow cycle is important context for understanding what follows and is also included for completeness since this is an area where geologically trained geomorphologists are driving key elements of the research agenda.

One of the assumptions behind this book is that the processes which drive the fluxes within and the reorganisation of sediment systems are a major influence on carbon cycling. If this is the case, then the developed techniques and gathered process-based knowledge of more than a century of geomorphological research will make a contribution to a fuller explanation of the terrestrial carbon cycle. Therefore, in Chapter 4 a range of key conceptual approaches which underpin modern geomorphological thinking are highlighted and the ways in which they can contribute to understanding of carbon cycling are explored.

Part II (Chapters 5 to 8 of this book) focusses in more detail on the fast carbon cycle and the ways in which geomorphological processes interact with vegetation and soil microbiota to cycle carbon through the terrestrial system. Two organising principles underpin the concept of the sediment cascade and the idea of a carbon landsystem.

The Sediment Cascade

In Figure 1.1, the fluvial system which is the primary conduit for the direct transfer of carbon from the continents to the oceans is represented by a simple line. This is in contrast to the detail on the land surface, which indicates a range of processes driving terrestrial carbon cycling. However, as briefly discussed above, the fluvial system is complex and dynamic, and the previous model of the fluvial system as a pipe, simply transporting carbon from hillslope to ocean cannot be sustained. One of the organisational principles of this book is the

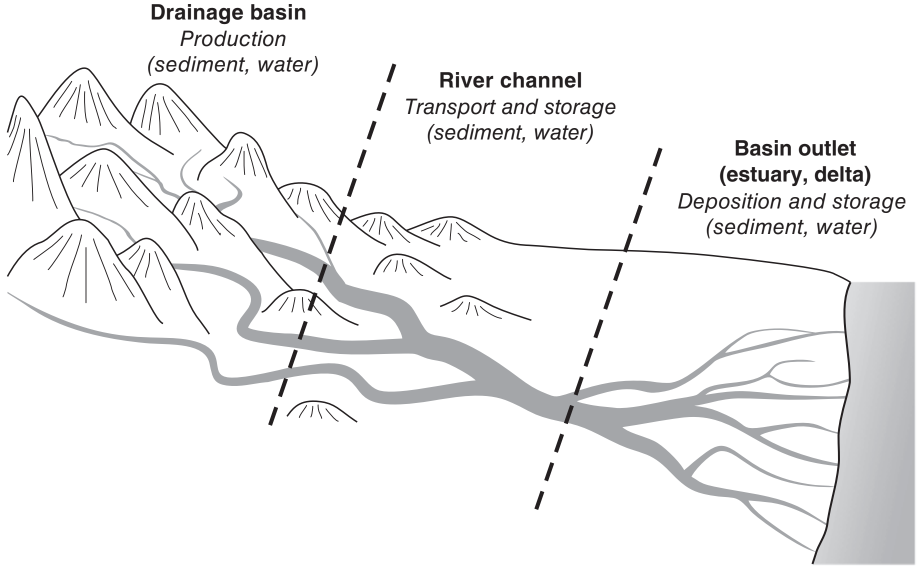

Figure 1.2 The sediment cascade. Source: After Schumm 1977. Reproduced with permission of The Blackburn Press.

sediment cascade (Burt and Allison 2010; Schumm 1977). Figure 1.2, from the paper by Schumm which initially outlined the concept, identifies key features of the cascade and defines a linear cascading system describing the flux of water and sediment through landscape systems, from production on hillslopes to deposition in oceans and estuaries. Figure 1.2 indicates that the key role of hillslopes and headwaters in the sediment system is the production of sediment, and the delivery of this material to downstream fluvial systems. In the context of organic carbon fluxes, the River Continuum Concept makes similar assumptions. However, as outlined in a recent analysis by Joyce et al. (2018), the flux of sediment through the upland sediment cascade involves both production of sediment through upland erosion, but also storage in a range of depositional landforms (Figure 1.3).

A full description of the flux of sediment and organic carbon through the landscape therefore requires analysis of all components of the sediment cascade, considering the production, storage and cycling of carbon. Chapters 5–8 review the literature on carbon cycling for four key components of the sediment cascade. These are hillslopes (Chapter 5), headwaters (Chapter 6), the fluvial system (Chapter 7) and estuaries/coasts (Chapter 8). For these specific contexts the chapters explore the interaction of geomorphological processes, vegetation and succession as a control on primary production and decomposition and mineralisation of organic carbon by the microbial system.

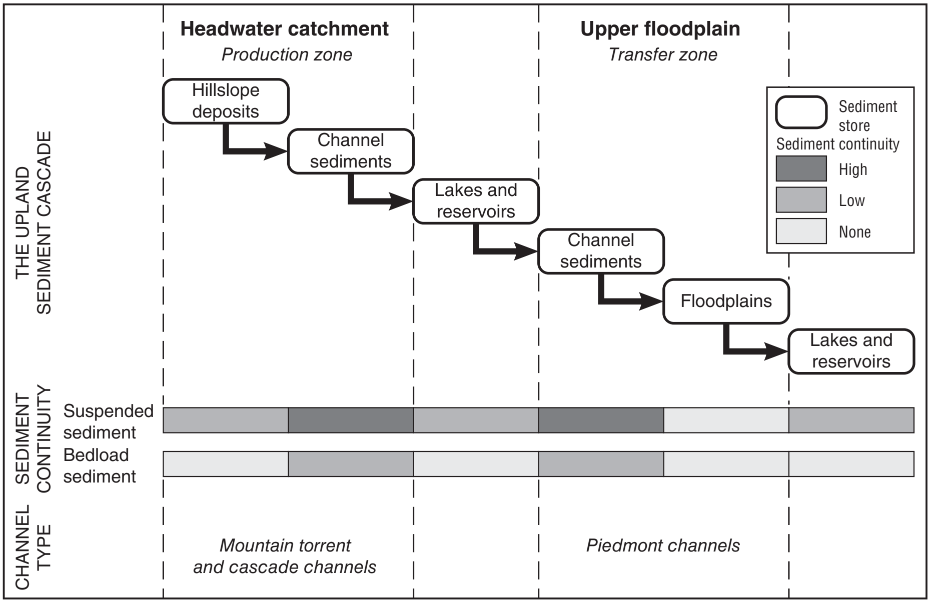

Figure 1.3 A model of the upland sediment indicating the complexity and continuity of sediment transfer in this sub-component of the wider cascade. Source: After Joyce et al. 2018 (https://doi.org/10.1016/j.geomorph.2018.05.002). Licensed by CCA 4.0.

The Carbon Landsystem

The review and synthesis of the literature in Chapters 5–8 aims to identify the primary carbon stores within each sub-component of the sediment cascade, and to analyse the key processes which drive translocation and transformation of organic carbon within the system. In the geomorphological literature, the term landsystem is used to describe conceptual models of synthetic landscapes that describe key landforms and the processes that drive material flux through the system and produce these characteristic landforms (e.g., Evans 2014). The analysis in this book builds from the assumption that the geomorphological context is not a boundary condition to the terrestrial carbon cycle, but is a dynamic driver of the flux of carbon through the sediment cascade, so that quantification of carbon flux requires integration of geomorphological, biological and microbiological processes. In this context, it is a short conceptual step to move beyond the landsystem as a description of characteristic geomorphologies to thinking about the carbon landsystem as the characteristic set of interactions between these three process types, which drive fluxes of carbon through depositional landforms at points along the sediment cascade. Chapters 5–8 attempt to characterise the carbon landsystem for key elements of the cascade.

Part III (Chapters 9 and 10 of this book) explores some of the implications of a geomorphological approach to understanding the carbon cycle from the perspective of the management of carbon landsystems, in order to mitigate anthropogenically driven increases in atmospheric carbon content. With the International Chronostratigraphic Commission looking likely to ratify a recommendation that the Anthropocene be recognised as a new geological epoch (Zalasiewicz et al. 2017), there is an emerging consensus that human action is the dominant control on environmental systems. As discussed above, one of the key drivers for developing an understanding of the functioning of carbon landsystems is to have the tools to actively manage these systems. Chapter 9 reviews progress in this direction. Finally, in Chapter 10 the benefits of integrating geomorphological understanding into our analysis of the terrestrial carbon cycle are summarised and conceptual and practical approaches to the concurrent analysis of biological, microbiological and geomorphological components of the carbon landsystem are proposed.