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25 YEARS OF PROGRESS IN PHYSICAL GEOGRAPHY: A PERSONAL VIEW OF ITS ANTECEDENTS AND TRAJECTORY

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ABSTRACT

This paper presents a very personal view of developments in Physical Geography up to the early 1990s and then in the last 25 years. In the latter period, four sub-areas (Biogeography, Climatology, Geomorphology, Hydrology) have dominated the discipline, with Glaciology and Pedology also receiving significant attention. The advent of remotely sensed data sets, new sensors for proximate monitoring, and analytical software have enabled research across many space scales with improving spatial and temporal resolution. New modelling approaches have been increasingly supported by field and laboratory experiments. Furthermore, investigations have become more applied and human-oriented. Three aspects of the last 25 years bear witness to the health, relevance and impact of the discipline: (i) increasingly collaborative, international and multi-disciplinary research; (ii) a trend towards application and professionalization; (iii) increasing engagement in 'citizen science' by developing and applying methods that involve volunteers in monitoring, analysing and interpreting vast geographical data sets.

CONTEXT

My career in physical geography dates back to 1966 when I started my undergraduate training at the University of Exeter. Since then I have remained firmly based as an academic within the British university system. This paper is a very personal and far from comprehensive view of how the discipline of physical geography has changed, emphasising the last 25 years or so. However, given the 50 year span of my experience, I start with a longer term perspective because many recent developments have their foundation in earlier

My personal perspective comes from my early career as a geographical hydrologist and the subsequent gradual expansion of my interests to encompass fluvial geomorphology, its physical and plant ecological context, and, most recently, the application of this science to the restoration and sustainable management of rivers. This means that mine is a British perspective, founded on freshwater, how it flows across and within the Earth's surface, interacts with sediments and plants, and drives the form and dynamics of river basins, valleys, floodplains and channels. While this paper inevitably reflects this perspective, I have tried to consider the broader nature of the discipline, the themes that it encompasses and that give it a coherent character. Furthermore, although I refer predominantly to work by physical geographers, I have scanned the environmental sciences more generally in order to maintain a robust commentary.

At the beginning of this century, I contributed to a review of the discipline (Gregory, Gurnell and Petts, 2002), where we suggested that physical geography had been divided traditionally into three science areas (biogeography, climatology, geomorphology (with hydrology)), which we considered to be becoming more integrated, building on central interests in a spatial-temporal and scientific analytical approach; on how natural environmental systems and forms evolve; and on how they are being increasingly influenced by human-environmental interactions. The trend of increasing integration of physical geography has been noted more recently by other authors (e.g Malanson et al., 2014, Day, 2017). Day (2017) came to this conclusion after reviewing the content of textbooks relevant to the physical geography undergraduate curriculum in universities in North America and the United Kingdom. However, he also concluded that there are currently six main physical geography science sub-areas: biogeography, climatology, geomorphology, glaciology, hydrology, pedology. Therefore, I have framed my exploration of the discipline around these six areas and have added a seventh, which emphasises human-dominated processes and environments.

To provide some insights into the development of the discipline prior to the last 25 years:

(i) I present a very selective list of some historical contributions that extend back into the nineteenth century and cover the period up to 1990. I also attempt to briefly summarise developments during (a) the nineteenth century, (b) from 1900 to 1960, (c) during the 1960s and 1970s and, lastly (d) during the 1980s to early 1990s, in part emphasising my particular areas of interest.

(ii) I then consider the period from 1990 to the present in greater detail. To provide some overview of broad developments in the discipline, (a) I present a content analysis of papers published in the journal Progress in Physical Geography for the 25 year period 1993-2017, since this journal provides reviews of developments across the discipline, and (b) I then highlight several themes which have emerged strongly over the last quarter century, illustrating these mainly from my own areas of research interest.

A BRIEF HISTORY OF THE DEVELOPMENT OF PHYSICAL GEOGRAPHY PRIOR TO 1990

60 publications to 1990

My original intention was to compile a maximum list of 50 influential research papers or textbooks written mainly by geographers but also representing other contributions that track the development of the discipline to 1990. However, having assembled a much longer list and attempted to prune it, I concluded that it was not possible to reach 50 without losing some very important contributions and producing an unbalanced list in relation to the seven areas of the discipline defined in the previous section. Therefore, the 60 references listed in Table 1 are selected to provide an historical vision of the nature and development of physical geography. I am sure that most readers will argue that I have omitted one or more fundamentally important contributions, but I hope that the main developmental trajectories in the discipline to 1990 are apparent from Table 1, and that at least some of the omissions are incorporated in the following text. To link to discussion in the text, Table 1 separates the 60 publications into groups representing the nineteenth century, 1900 to 1960, the 1960s and 1970s, and finally the 1980s.

I feel incredibly fortunate that I started my geographical training during the 1960s, because this decade saw the beginning of truly transformative changes in the discipline of physical geography and thus marks a natural boundary in Table 1. Prior to the 1960s, much of the focus of physical geographers and scientists in cognate disciplines was on observing and describing the form and structure of landscapes and the organisms they supported at a range of spatial scales in order to conceptualise how these had developed and the key controlling processes, usually over long periods of time. Despite a number of previous examples, the 1960s saw the widespread uptake of formal frameworks and methods for quantifying processes as well as forms and their linkages, providing the foundation of 'modern' physical geography in the ensuing decades.

Nineteenth century foundations

Several fundamental works were published during the nineteenth century that provided a firm foundation for the development of the environmental sciences including physical geography. Most notable were the many contributions of Charles Darwin. In Table 1, in addition to 'On the origin of species', I list his work on earth worms which provided an important foundation for biogeographical, pedological and geomorphological research. Stoddart (1966) provides an informative review of Darwin's enormous impact on geography. In addition to Darwin's contributions are the works of Lyell, Agassiz, Davis and Wallace, which can be argued to provide the bases for the development of geomorphology in general, and glacial geomorphology, fluvial geomorphology and zoogeography in particular. Further, Marsh's (1864) early warnings about the ability of humans to severely impact their environment provides a precursor to research on humans as environmental agents. However, from my perspective, Huxley's (1877) book entitled 'Physiography' (his interpretation of 'Physical Geography') was perhaps the most important for the discipline as it conceptualised its multi-scale nature. Using the case study of the Thames basin, Huxley "endeavoured to show that the application of the plainest and simplest processes of reasoning (to an observed phenomenon) show, lying beneath it, a cause, which again suggests another; until step by step, the conviction dawns on the learner that, to attain even an elementary conception of what goes on in his parish, he must know something about the universe; that the pebble he kicks aside would not be what it is and where it is, unless a particular chapter of the earth's history…had been exactly what it was" (Huxley, 1877, p vii). This concept of the way in which processes interact across time and space to drive landscape development is truly integrative and underpins subsequent investigations aimed at understanding how landscape development varies across the earth's surface and through time.

1900-1960 – from landform to process

During the first 60 years of the twentieth century, geography became increasingly recognised as a discrete discipline, and major advances were achieved in all branches of physical geography (Table 1). Concepts of landscape and landform evolution continued to evolve (e.g. Horton, 1942, King, 1953, Linton, 1955) but there was an increasing emphasis on causal processes (e.g. Clements, 1916, Milne, 1936, Hursh and Brater, 1941, Lindeman, 1942, Elton, 1958, Corbel, 1959) with attempts to understand the mechanics of processes and to link them to forms through measurement and quantitative analysis (e.g. Bagnold, 1941, Lamb, 1950, Leopold and Maddock, 1953, Strahler, 1954). At the same time, the impacts of humans on their environment and *vice versa* attracted concern and investigation (e.g. White, 1945, Sundborg, 1951, Carson, 1952). 'Man's role in changing the face of the Earth', edited by Thomas (1956), was a landmark in summarising the range and complexity of the impacts of humans on their environment.

The 1960s and 1970s – a period of rapid change

During the 1960s, physical geographers started to consider landscapes within the framework of General Systems Theory (Chorley, 1962, Chorley and Haggett, 1967), laying the foundation for the discipline to contribute to 'Earth System Science'. Over the next twenty years, the study of physical processes emerged as a central focus in physical geography, not only through the conceptualisation of how processes and forms were linked within open systems (Chorley and Kennedy, 1971), but increasingly through the development and application of techniques to measure and model phenomena (e.g. Beven and Kirkby, 1979, Mosely and Zimpfer, 1978, Wilson and Kirkby, 1975). The presence of these trends across the sub-areas of physical geography are witnessed by integrative texts (e.g. Gregory and Walling, 1973, Sugden and John, 1976, Watts, 1971).

During the 1960s and 1970s, changes in climate were being demonstrated quantitatively through the analysis of climatological records (e.g. Manley 1974) and distinct human impacts on climate were stressed (e.g. Chandler, 1965, Manabe and Wetherald, 1975). Other studies of environmental change increasingly depended upon field and laboratory methods that established environmental chronologies. Palynology was rapidly adopted by physical geographers to support interpretation of long term changes in vegetation attributable to climate and human impacts (e.g. Oldfield, 1963), and other 'dating' techniques were starting to emerge based on the analysis of sediment properties (e.g. Appleby and Oldfield, 1978, Molyneux et al., 1972). Furthermore, the launch in 1972 of the first Earth Resources Technology Satellite (subsequently renamed Landsat) marked the beginning of an era where vast data sets provided repeated spatial monitoring to complement point measurements at a higher temporal resolution than was previously available from map and air photograph archives.

In my area of interest, an increasing emphasis on water-related processes was reflected in the publication of Leopold, Wolman and Miller's (1964) 'Fluvial Processes in Geomorphology', and the concurrent emergence of hydrology as a new science area within physical geography. The first hydrology textbook aimed at physical geographers was published (‘Principles of Hydrology’, Ward, 1967) as was the first text that integrated concepts with measurement techniques and modelling approaches for the study of hydrology and fluvial geomorphology (‘Drainage Basin Form and Process: a geomorphological approach’, Gregory and Walling, 1973). As time progressed, geographical hydrology and fluvial geomorphology became increasingly closely integrated, with the term ‘hydrogeomorphology’ proposed (Scheidegger, 1973, Gregory, 1979). Integrating research considered process-form linkages and feedbacks, encompassing both threshold and equilibrium behaviour across widely varying space and time scales (from seconds to millennia, from particles to regions). The work of Stanley A. Schumm was fundamental to these developments (e.g. Schumm and Lichty, 1965), and his book on ‘The Fluvial System’ (Schumm, 1978) provides an excellent, integrated overview of his contribution as well as illustrating the way in which the discipline was changing at this time. In addition, physical geographers were researching process-landform linkages in different water environments, from those where water is mainly frozen (e.g. Sugden and John, 1976, French, 1976) to those where it is scarce (e.g. Cooke and Warren, 1973).

Contemporary hydrogeomorphological research was complemented by analyses of environmental change specifically directed towards river systems and catchments. For example, Wolman (1967), Hammer (1972) and Knox (1977) published important contributions on the hydrogeomorphological responses of stream channels to human actions. While *in situ* measurements of sediment processes (erosion pins and plots) had started to be widely applied, particularly in relation to estimating the impacts of human activities on soil erosion (e.g. Universal Soil Loss Equation, Wischmeier and Smith, 1960), methods to ‘fingerprint’ sediment sources to river systems were rapidly developing, based upon their geochemical, mineralogical, and mineral magnetic signatures. The identification of the source of sediments found in rivers from laboratory analyses of their ‘fingerprints’ allowed researchers to estimate the relative quantitative contribution of different catchment sediment sources to river sediment loads (e.g. Walling et al., 1979).

Within water-related areas of physical geography, international influences beyond the discipline gave impetus to disciplinary developments. UNESCO’s international hydrological programmes were crucial, with the first of these commencing during the 1960s. The International Hydrological Decade (1965-1975) encouraged education and training, standardisation of measurement techniques and units, and basic data collection across the hydrological sciences. Importantly, ‘basic data collection’ involved the establishment of representative and experimental drainage basins instrumented to study the impact of catchment characteristics and land use changes on the hydrological cycle. The establishment of these basins was a springboard for geographical hydrological research encompassing field measurements, experiments and modelling (e.g. Kirkby, 1978), and for a focus on the impact of humans on hydrological systems (Gregory and Walling, 1979, Hollis, 1979). At the same time, there was a growing interest in the application of all areas of physical geography to resolving environmental management issues (e.g. Cooke and Doornkamp, 1974).

The 1980s – consolidation and technological advance

The 1980s saw consolidation and progress in aspects of the discipline that had emerged in the 1960s and 1970s, building on an increasing recognition of the multidisciplinary, multi-dimensional nature of environmental systems (e.g. Vannote et al., 1981), but several additional and distinct themes can be recognised.

Although previous decades saw the beginnings of research on the impacts of human activities, focussing mainly on physical processes and forms, research in this area intensified in the 1980s. It embraced a wider range of human-environment interactions and feedbacks, taking advantage of the outputs from monitoring programmes set up in the preceding decades, and, following Brunsden and Thornes (1979), it highlighted the sensitivity of particular landscapes to change, whether driven by natural or human-induced phenomena (Thomas and Allison, 1993). In my area of interest, there were key developments in the quantification and characterisation of how humans had both directly and indirectly affected hydrogeomorphological processes. Building on Knox's (1977) work, case studies of river morphological change emerged that synthesised and analysed historical information sources (e.g. Petts et al., 1989). Trimble's (1983) investigation of sediments and human artifacts provided the first detailed catchment-scale analysis of the effects of agriculture on the sediment budget. Trimble illustrated in a single catchment how sediment, released from fields, followed a sequence of deposition, storage and remobilisation as it passed through the catchment system, altering the stratigraphy and morphology of valley bottoms and floodplains. Developing techniques of sediment fingerprinting allowed quantification of such sediment movements through drainage basins in a series of erosion-transfer-storage steps, allowing sediment budgets to be defined across multiple time and space scales even where changes were morphologically quite subtle (Walling 1983).

Research in different environmental settings, subject to different climates and human pressures, revealed the crucial importance of plants and other living organisms (e.g. Osterkamp and Hupp, 1984, Viles, 1988) as well as their management (Graf, 1978) for water and sediment delivery and transfer through river systems and associated landform development (Thornes, 1990), giving rise to a new area for research, 'Biogeomorphology'.

The far-reaching hydrological, geomorphological and ecological consequences of human interventions in river systems were also recognised, including the impacts of river channelization (Brookes, 1988) and the installation and management of river impoundments (Petts, 1984). Petts (1984) volume is particularly notable because it conceptualises complex sequences of both spatial and temporal changes induced by dams and river flow regulation encompassing interactions and feedbacks among hydrological, geomorphological and ecological processes.

The impacts of physical processes on humans also became a major focus of research, particularly in relation to environmental hazards (e.g. landslides -Brunsden and Prior, 1984; floods – Baker et al., 1988). One emerging topic within fluvial geomorphology, initiated in part by flood hazard research, was the presence of wood in river systems. Sedell and Frogatt (1984) illustrated the dramatic geomorphological and ecological consequences of wood removal from the Willamette river, USA, to reduce flood risks and support human activities such as agriculture, navigation, timber exploitation. At the same time, pioneering research on the environmental role of wood by a multi-disciplinary team, including physical geographers, in the Pacific northwest of the USA (Harmon et al., 1984) initiated an important debate about large wood. The entire set of biogeochemical, hydrogeomorphological, ecological, conservation and management issues related to floodplain forests and wood soon attracted research attention. Furthermore, work on this topic in the UK, broadened the consideration of wood and trees to include other living vegetation as a crucial element of catchment and river hydrogeomorphology (e.g. Gurnell and Gregory, 1987, 1988).

The 1980s saw major advances in process-form monitoring at the earth's surface (e.g. Goudie et al., 1990) with new proximate monitoring technologies leading to increasingly sophisticated process-form understanding (e.g. Clifford, 1993). There was also an enormous influx of data from sensors mounted on aircraft and satellite platforms (Campbell, 1996). The need to assimilate, analyse and integrate data from these sources as well as more traditional ones, notably maps, resulted in probably the most important technological advance for geography as a whole in the 1990s. This was the availability of Geographical Information Systems (GIS) software that could store, integrate and analyse disparate spatial data sets and present the results in an accessible format (Burrough and McDonnell, 1998, Maguire et al., 1991). As physical geographers developed more sophisticated models, these were often linked to a GIS, which managed the input data and displayed the analytical outputs as well as delivering some of the data manipulations.

Finally, a crucial external factor in the development of physical geography research during the 1980s was significant funding for interdisciplinary international environmental research projects within (and beyond) Europe. The Framework Programmes for Research and Technological Development of the European Union / European Commission (FP1 commenced in 1984) provided an important new funding source. At the same time and associated with a trend towards increasing application of research results and methods, was the beginning of the professionalization of physical geography. For example, Richards et al. (1987) make the case for the application of fluvial geomorphology to the appraisal of engineering projects, while in 1979, Geomorphological Services Ltd was set up by a group of UK academic geomorphologists to provide consultancy services.

Thus the 1980s saw physical geography as an emerging scientific discipline that contributed vital knowledge and research methods to the investigation of multi-disciplinary environmental issues and to the provision of professional services capable of supporting the resolution and management of environmental problems.

THE LAST 25 YEARS: 1990 TO THE PRESENT

An overview

The last 25 years are too close for me to give a confident, spontaneous and broad overview of the development of physical geography. Therefore, as a starting point, I have undertaken a content analysis of publications in a journal that aims to review the discipline: Progress in

Physical Geography. My analysis focusses on 833 papers published in the years 1993 to 2017, inclusive, excluding editorials and book reviews. It represents my personal judgements and interpretations of the content of these publications. These interpretations are very unlikely to be perfectly replicated if somebody else were to undertake the analysis. However, I believe that the broad outcomes from such an analysis would be similar and so I hope it provides a useful perspective on the contemporary state of the discipline.

By considering the titles, abstracts, and in some cases the body text of these publications, I first allocated them to one or two of the sub-areas considered in Table 1 (i.e. Biogeography, Climatology, Geomorphology, Glaciology, Hydrology, Pedology). I excluded the 'human' subarea at this stage because human impacts could relate to any of these six sub-areas. Furthermore, in relation to 'glaciology', I occasionally allowed allocation to a third sub-area. This was because papers with a central focus on frozen water often also involve a strong emphasis on hydrology, climatology and/or geomorphology (and recently biogeography). Therefore, where glaciology papers had a strong emphasis on several of these other sub-areas, I allowed up two to be added to that of glaciology.

Figure 1 illustrates the percentage of publications addressing the six sub-areas as well as those that encompass multiple sub-areas (i.e. more than two, apart from where glaciology is the third) and those (mainly methods papers) that are not explicitly related to any specific sub-area(s). Figure 1 illustrates that the largest proportion of publications focus on geomorphology, with biogeography, climatology and hydrology showing similar, quite high, proportions and the remaining categories representing similar, small, proportions. Importantly, although there are high fluctuations in the relative importance of the sub-areas between years, no clear temporal trends are apparent. Therefore, I present the rest of my content analysis in aggregate across the 25 year period, starting with the subareas already considered in Figure 1 to confirm the already-summarised balance among them (Figure 2A) and thus the apparent dominance of biogeography, climatology, geomorphology and hydrology within the discipline.

Given the importance of time, space and environmental setting to any geographical analysis, Figure 2 provides summary information on these aspects, where they are clearly emphasised in the publications. Since the journal publishes review papers, many are very broad, cutting across time and space scales and referring to a range of environmental settings. However, the content analysis identified those papers that highlighted specific scales and settings, allowing up to two timescales, one space scale and one environmental setting to be identified for each publication.

Most of the publications referencing timescales (Figure 2B) emphasise Contemporary to Decadal scales, reflecting time periods over which detailed scientific monitoring of processes has occurred as well as the emergence of data sets captured from airplanes and satellites. Investigations over longer timescales are less numerous and are usually dependent upon dating and interpreting historical artifacts and records such as maps, photographs, paintings and documents (Centuries) or bedrock, sediments and preserved biological materials (Centuries and Millenia+ - thousands of years and longer timescales).

As with time scales, many review papers encompass a wide range of space scales. However, where space scales are clearly indicated, the most frequently-considered (Figure 2C) are Landscape (including river catchments) to Regional scales, although a good proportion of publications focus on smaller (Local) areas. Some publications consider processes at a Global scale (particularly in climatology), and a few (Other) consider other planets.

In relation to environmental setting (Figure 2D), a long list of different settings was aggregated into the classes depicted in the bar graph, the majority (65%) of the reviewed papers encompassed a variety of settings or were not specific on this issue. At least three properties of the remaining 35% (Figure 2D) are noteworthy, the many different settings that provide the focus for individual publications; the relatively small number of papers that specifically refer to the humid temperate (probably because it is the home of many of the authors contributing to the journal and so is an implicit rather than explicit context of their writing), and the emergence of the human-dominated urban environment as a setting for physical geography research.

To explore the nature of the research in greater depth, publications were allocated to up to two process themes and up to two methods groups, when these were specifically relevant to the theme of a paper (Figure 3). As with Figure 2D, a long list of key words were aggregated into the bars shown in Figure 3. Although sub-groups of bars are presented in Figures 3A and B, these are provided to aid visual interpretation of what was a single aggregate analysis.

In relation to Figure 3A, Biological processes were identified where there was limited or no reference to other (non-biological) processes, whereas Ecological processes represented an integration of the biota and related processes with other environmental processes to support understanding of different aspects of ecology. Biogeochemical refers to complex local investigations of chemical, biological and geophysical processes and their interactions, usually demanding a high level and quantity of laboratory analysis. Furthermore, the bars depicting process groups are concerned with either a narrow group of related processes (e.g. Aeolian) or processes operating in a very specific environment (e.g. Marine), whereas the bars for process context refer to processes that link environments (e.g. Atmosphere-surface exchange (of water / energy)); operate within specific environments (Human (e.g. agriculture, urban), Soil development, Sediment dynamics (e.g. in rivers, deserts); or are extreme processes that impact on humans (Natural hazards). In relation to process groups, the most frequent are papers concerned with Ecological processes that provide links between the biota and their environment. In relation to process context, the human context is the most frequent, indicative of expanding research relevant to the ‘Anthropocene’.

Figure 3B summarises the types of methods explicitly emphasised and developed in 43% of the publications analysed, including those that were entirely concerned with methods. In terms of measurements, the dominance of Remote measurements (from ground, air and satellite platforms) is clearly apparent, although direct (Proximate) measurements and Dating methods (including absolute and relative dating as well as the use of proxies) are also widely reviewed. Field and Laboratory experiments (i.e. measurements of manipulated conditions in comparison with controlled conditions) are a small component of the methods reviewed, but are probably an indication of an important tool for future research. Data synthesis and GIS, whereby different spatial (and multi-temporal) data sets are integrated to identify emergent patterns, provides an important focus in a significant number of publications. Here, I include publications on digital elevation models but I confine papers concerning basic 'image processing' to the Remote measurement category. In addition to such data synthesis, papers which set out to categorise (Classification) or model (Conceptual, Statistical, Mechanistic) are also considered. While all of the three modelling approaches identify relationships among processes and sometimes with forms, I identify Statistical models as those which estimate relationships from empirical observations using statistical analysis; Mechanistic models as those that start with a proposed (usually physically-based) relationship or set of relationships between variables, even if these relationships are then fine-tune using statistical methods. Finally, my restricted definition of a Conceptual model is one which conceptualises how a set of processes and forms may be related, usually based on empirical field observations, but does not quantify them. It is interesting to note the quite widespread use of Data synthesis and GIS and the three types of modelling in the analysed publications. The last group of bars in Figure 3B refers to explicit links with social science. This small group of papers with a 'social science' content identifies a second emergent group of methods that will be increasingly relevant as physical geography becomes more applied and human-focused.

Finally, whilst undertaking the content analysis, I encountered publications on a number of topics that have only emerged as a contributor to physical geography research in the last 25 years. Genetic and molecular methods are emerging tools; species invasions, extinctions and the spread of diseases are emerging processes; and war is an emerging environmental setting for physical geographical study.

In summary, the content analysis reveals some important aspects of contemporary physical geography that distinguish the last 25 years from preceding decades:

(i) Biogeography, Climatology, Geomorphology and Hydrology continue to dominate the discipline, but many publications focus on two or more of these areas as witnessed by the importance of ecological process investigations.

(ii) Glaciology and Pedology have received less attention. In addition to its strong links with Hydrology and Geomorphology, Glaciology is becoming increasingly linked to Climatology in the context of global climate change, often making it a multidisciplinary application of these three sub-areas with recent inclusion of the fourth, Biogeogeography. In a similar way, much of the work in Pedology is linked to other sub-areas, in particular forming part of the human-oriented body of work that is being undertaken in relation to the main four sub-areas of Physical Geography

(iii) With the advent of enormous quantities of remotely sensed data and methods devised to analyse and synthesise such data sets, including GIS, physical geographers are working at increasing spatial scales (particularly landscape and regional scales) as well as incorporating data from new sensors and instruments. Nevertheless, proximate ground measurements remain important, not least because they serve to calibrate remotely-sensed data. Furthermore, methods to analyse historical and longer-term changes remain crucial to documenting trajectories of environmental changes.

(iv) Different modelling approaches are being adopted and physical geographers are starting to conduct truly experimental work to support this modelling. Experimental work is beginning to emerge as a focus in field and laboratory work, including large experiments in laboratory flumes.

(v) Not only are physical geographers investigating a wide variety of natural environments but over the last 25 years investigations have become more applied and human-oriented. Indeed, the urban environment has become central to much physical geography research as have agricultural landscapes. The early emergence of papers that explicitly include aspects of social science are a further indication of an increasing human-oriented focus.

Illustrations of the trends identified from content analysis

To underpin and illustrate trends (iii), (iv) and (v) identified through the content analysis, this section considers them in relation to my areas of research interest in the hydrology, geomorphology and plant ecology of river systems.

In relation to trend (iii) and following the arrival of satellite remote sensing in the 1980s, data sets of increasing temporal, spatial and spectral resolution have become available over the last 25 years. Complementing the data sets, captured mainly from aircraft and satellites, there have been major advances in the precision and temporal resolution of proximate process measurements (Kondolf and Piégay, 2016). Indeed, 'remote' and 'proximate' measurements have converged at fine to intermediate scales to produce extremely high resolution information on processes, forms and morphological changes (e.g. Lane et al., 2003; Brasington et al., 2012). All of these new data sets have fuelled a revolution in the exploration of the physical geography of the Earth's surface since 1990, with remote sensing techniques allowing research to extend to other planets. In relation to my research interests concerning hydrological, fluvial geomorphological and plant ecological processes, Carbonneau and Piégay (2012) and Bizzi et al. (2016) provide recent revues of the types of remotely-sensed data that are available and their potential for extracting hydrogeomorphological characteristics of catchments, floodplains and rivers. By combining these data sets with information from more traditional sources such as air photographs and proximate ground measurements, it is becoming possible to investigate physical forms and processes across global to patch scales and to generate new, often interdisciplinary perspectives on their interactions (e.g. Bertoldi et al., 2011 a, b). This raises the potential to extract signatures of processes at multiple spatial scales to support understanding of the penetration of processes across landscapes (e.g. Gurnell et al., 2016a). Nevertheless, field work remains an essential element in developing understanding of processes and their relationship with forms, not only because of the requirement for proximate measurements to calibrate remotely-sensed data sets, but also because field work allows direct observation of phenomena and the potential to develop understanding from field measurements and observations through inductive reasoning. As noted by Church (2013, p184) 'Recent technological developments have enhanced our ability to comprehend the landscape system, but the effort will surely require comprehensive field experience if we are to regain the whole landscape view of the early field workers'.

For simplicity, I illustrate trend (iv) in relation to one area of hydrogeomorphology that has attracted enormous recent attention: the importance of vegetation as a third control with water and sediment on the morphodynamics of river and floodplain environments. This area of research has benefitted enormously from the new data sources described in the previous paragraph and builds on research in the 1980s on large (mainly dead) wood within fluvial systems. In the last 25 years, mutual interactions and feedbacks among living vegetation and fluvial processes have been recognised; revealing the key, active role of vegetation in controlling and stabilising landform development. This work is part of a wider, emerging focus within geomorphology: 'the search for a topographic signature of life' (Dietrich and Perron, 2006) that requires multi-method, multi-scale research, incorporating expertise from cognate disciplines. Over the last 25 years, both conceptual understanding and modelling have advanced dramatically, building on important early work by, for example, Gregory et al. (1991) and Kirkby (1995). Advances in this area have been extremely rapid and have been directed at all spatial scales from patch to landscape (for a recent review see Solari et al., 2017). Perhaps the most exciting dimension of this research is that scientists are combining conceptual and mechanistic models, laboratory and field experiments, and empirical field observations in their investigations. This multi-pronged approach has resulted in the development of models applicable to entire landscapes (e.g. Stewart et al., 2014), river corridors (e.g. Camporeale and Ridolfi, 2010, Bertoldi et al., 2015, Gurnell et al., 2016b, van Oorshot et al., 2016), river channels (e.g. Murray and Paola, 2003, Braudrick et al., 2009, Eaton and Giles, 2009, Parker et al., 2001), river banks (Pollen and Simon, 2005, Polvi et al., 2014) and soil patches (De Baets et al., 2008). While much of this research is concerned with timescales from days to decades, there is also a fascinating emerging focus on longer timescales, recognising the fact that vegetation has probably been a significant river geomorphological control factor since the Late Silurian (Corenblit et al., 2015).

Building on early work in the 1990s, applied physical geography research is another strongly emerging theme (trend (v)). Recent reviews consider the physical geography (Ellis, 2017), biogeography (Kenneth, 2015) and geomorphology (Brown et al., 2017) of the 'Anthropocene': the recent and current period during which human influence on the Earth dominates over natural processes. Applied physical geography research seeks to understand direct and indirect human impacts and feedbacks within environmental systems, enabling this knowledge to be incorporated into improved management and restoration activities. In my area of interest, the physical and ecological functioning of particular human-dominated landscapes such as urban (Gurnell et al., 2005) and cultivated (Morgan et al., 1998, Poesen et al., 2003) areas, and the environmental impacts of alien (e.g. Corenblit et al., 2014, Perkins et al., 2016) and reintroduced species (Puttock et al., 2016) are some of the many applied topics that are receiving the attention of physical geographers. Fluvial geomorphological approaches are being developed across the World for the characterisation, assessment and management of rivers (e.g. Brierley and Fryirs, 2005, Rinaldi et al., 2015). This is complemented by applied research establishing the impacts of changing climate, land cover and management on water resources (e.g. Huntington, 2006, Kundzewicz et al., 2007), river flow regimes and extremes (e.g. Vörösmarty et al., 2010, Wilby and Keenan, 2012), river morphodynamics and ecology (e.g. Rood et al., 2005, Poff et al., 2006, Monk et al., 2008), the nature and maintenance of river ecosystem services (Constanza et al., 2017) and the overall health and resilience of rivers in an increasingly human-modified world (Meyer, 1997, Naiman et al., 2002, Chapin et al., 2009).

International diversification, professional physical geographers, and the advent of citizen science

To conclude my evaluation of the last 25 years, I should like to highlight three further themes that I believe have come to characterise physical geography.

Many of the publications cited in the previous section bear witness to the fact that international groups of scientists are increasingly tackling research problems in physical geography and related disciplines. The emergence over recent decades of major international research collaborations is strengthening the profile of physical geography and is supporting the participation of physical geographers within multidisciplinary endeavours. Although this appears to be a global phenomenon, within Europe from the 1980s this trend has been amplified by the availability of significant international funds, allowing physical geography researchers to participate in not only multidisciplinary but also multicultural research investigations of both fundamental and applied issues at a continental scale. Furthermore, the increasing ease of international travel allows teams of scientists to address issues that are particularly pressing in certain biogeographical regions regardless of their geographical proximity to the researcher's home laboratories.

As previously discussed, there has been a marked trend towards applied research that dates back to the 1970s. However, demonstrable 'professionalization' of physical geography is a more recent phenomenon. The Royal Geographical Society has responded to this with the development of a Chartered Geographer accreditation, which is awarded to those 'with competence, experience and professionalism in the use of geographical knowledge, understanding and skills in the workplace'. For physical geographers, it is possible to seek accreditation as a C. Geog (Geomorph) indicating that the qualification specifically applies to the field of geomorphology. In my area of expertise, much of this professionalization can be linked to environmental directives of the European Union, particularly the Water Framework (2000) and the Floods (2004) Directives. Prior to 1990, few physical geographers were working in environmental consultancy, government environmental agencies or environmental NGOs, but now the opportunities to work in 'hydromorphology' (hydrology and fluvial geomorphology) are outstripping the supply of suitably qualified people. This is generating a prominent profile for the discipline and the satisfaction that physical geographers are really 'making a difference'.

A final, fascinating trend is the very recent emergence of 'Citizen Science'. The enormous data sets that can be generated by volunteers (Walker et al., 2016), provide a potentially revolutionary contribution to understanding environmental issues, problems and processes (Roberts 2016), although the quality of such data needs to be carefully evaluated and managed (Gollan et al., 2012, Hadj-Hammou et al., 2017). In my area of interest, enthusiastic, active, volunteer scientists are participating in data gathering, assimilation and interpretation to contribute to the assessment, conservation and management of rivers (Smith *et al*. 2014; Huddart *et al*. 2016). Litter, including microplastics, is the focus of numerous citizen science surveys (e.g. Rech et al., 2015, Bosker et al., 2017, Vincent et al., 2017). Freshwater environment survey techniques have been developed specifically for volunteers to assess water quality, through either direct (e.g. Loiselle, 2016; Bannatyne et al., 2017) or indirect, biologically-based (Di Fiore and Fitch 2016, Kelly et al., 2016) assessment methods. A wide variety of species information is also being collected, including information on problem species and issues such as phytoplankton blooms (Castilla et al., 2015). Citizen science data sets are also contributing to both catchment (Starkey et al., 2017) and reach scale characterisation and physical assessment (e.g. Shuker et al., 2017). Physical geographers are widely involved in driving these activities, but perhaps the most exciting area for future research and innovation is in the analysis of these inherently geographical data sets. Creative analysis of vast volunteer data sets, integrated with the more spatially and temporally limited data sets captured by professional river managers, presents a significant challenge but the rewards include enhanced monitoring, characterisation, modelling and understanding of environmental systems.

CONCLUDING REMARKS

The last twenty-five years have seen the discipline of physical geography emerge not only as an important framework for fundamental scientific research but also as central to environmental assessment, management and rehabilitation. While many of the elements of current activity can be traced back to earlier decades, the pace of expansion, diversification, integration and application is remarkable.

Not only is the discipline increasingly strong and integrated, but it is contributing to major multidisciplinary research programmes. We have moved from speculating on how landscapes function, to measuring and monitoring how they function with increasing accuracy and resolution. Now as we couple these measurements with models based on increasingly sophisticated multidisciplinary understanding, we enter an era of major potential breakthroughs. The most pressing research challenge is to develop enhanced ways of incorporating longer time scales to truly grasp how landscapes develop in all four dimensions.

Furthermore, the discipline is becoming more applied, professional and ‘relevant’. It is spawning a new generation of professional physical geographers tackling mounting real-world challenges and at the same time, it is engaging with citizen scientists to gain more comprehensive spatial and temporal monitoring of environmental systems and to provide early warnings of where problems are arising.

Based on these foundations, the future looks bright for the discipline of physical geography, but arguably equally exciting are the strong pointers towards links with human geographers and other social and economic scientists (Goudie, 2017, Richards and Clifford, 2008). Perhaps the upcoming decades will see the emergence of applied geography as important integrating theme for geography as a whole?

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Wilson, A.G. and Kirkby, M.J. 1975. Mathematics for geographers and planners. Clarendon Press, UK.

Wischmeier, W.H., and Smith, D.D. 1960. A universal soil-loss equation to guide conservation farm planning. *Transactions of the S*ixth *International Congress of Soil Science*, 418-425.

Table 1 60 publications, mainly by geographers but also highly influential contributions from other disciplines, that illustrate the historical trajectory of development of seven sub-areas of the discipline.

Author	Date	Title	Source	Biogeography	Climatology	Geomorphology	Hydrology	Glaciology	Pedology	Human
Lyell, C	1830-33	Principles of Geology, Being an Attempt to Explain the Former Changes of the Earth's Surface, by Reference to Causes Now in Operation	London: Murray	√	√	√				
Agassiz, L.	1840	Études sur les glaciers	Neuchatel: Jent et Gassmann			√		√		
Darwin, C.	1859	On the origin of species	London: John Murray	√						
Marsh, G.P.	1864	Man and Nature or Physical Geography as modified by human action	New York, Charles Scribner							√
Wallace, A.R.	1876	The geographical distribution of animals	London: MacMillan	√						
Huxley, T.H.	1877	Physiography: An introduction to the study of nature	London: MacMillan	√	√	√	√	√		
Darwin, C.	1881	The formation of vegetable mould through the action of worms, with observations on their habits	London: John Murray	√		√			√	
Davis, W.M.	1899	The geographical cycle	The Geographical Journal 14: 481–494			√				
Clements, F.E.	1916	Plant succession: an analysis of the development of vegetation	Carnegie Institution of Washington, Publication 242, Washington, 512pp.	√						
Milne, G.	1936	Normal erosion as a factor in soil profile development	Nature 138: 548–549			√			√	
Bagnold, R.A.	1941	The physics of blown sand and desert dunes	London: Methuen			√				
Hursh, C.R., Brater, E.F.	1941	Separating storm-hydrographs from small drainage-areas into surface- and subsurface-flow	Transactions of the American Geophysical Union 22: 863-871				√			
Lindeman, R.L.	1942	The trophic-dynamic aspect of ecology	Ecology 23: 399-418	√						

Horton, R.E.	1945	Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology	Bulletin of the Geological Society of America 56: 275-370			√				
White, G.F.	1945	Human adjustment to floods	Research Paper 29. Department of Geography, University of Chicago				√			√
Woolridge, S.W.	1949	Geomorphology and soil science	Journal of Soil Science 1: 31–34			√			√	
Lamb, H.H	1950	Types and spells of weather around the year in the British Isles	Quarterly Journal of the Royal Meteorological Society 76: 393-438		√					
Sundborg, Å.	1951	Climatological studies in Uppsala with special regard to the temperature conditions in the urban area	Geographica 22		√					√
Carson, R.L.	1952	Silent spring	New York: Houghton Mifflin	√						√
King, L.C.	1953	Canons of landscape evolution	Bulletin of the Geological Society of America 64: 721-752			√				
Leopold, L.B., Maddock, T.M.	1953	The hydraulic geometry of stream channels and some physiographic implications	US Geological Survey Professional Paper 252			√				
Emiliani, C.	1955	Pleistocene temperatures	Journal of Geology 63, 538-78		√					
Linton, D.L.	1955	The problem of tors	The Geographical Journal 121: 470-87			√				
Thomas, W.L. (ed.)	1956	Man's role in changing the face of the Earth	Chicago: University of Chicago Press	√	√	√	√		√	√
Washburn, A.L.	1956	Classification of patterned ground and review of suggested origins	Bulletin of the Geological Society of America 67(7): 823–865			√				
Elton, C.S.	1958	The ecology of invasions by animals and plants	London: Methuen	√						
Corbel, J.	1959	Erosion en terrain calcaire (vitesse d'érosion et morphologie)	Annales de Géographie 68: 97—120			√				
Rapp, A.	1960	Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia	Geografiska Annaler 42: 71-200			√				
Chorley, R.J.	1962	Geomorphology and General Systems Theory	US Geological Survey Professional Paper 500-B			√				
Yatsu, E.	1962	Rock control in geomorphology	Tokyo: Sozosha			√				
Kamb, B., LaChapelle, E.	1964	Direct observation of the mechanism of glacier sliding over bedrock	Journal of Glaciology 5: 159-172				√	√		
Leopold, L.B., Wolman, M.G., Miller, J.P.	1964	Fluvial Processes in Geomorphology	San Francisco: Freeman				√			

Chandler, T.J.	1965	The climate of London	London: Hutchinson		√					
Schumm, S.A., Lichty, R.W.	1965	Time, space and causality in geomorphology	American Journal of Science 263: 110-119			√				
Hewlett, J.D., Hibbert, A.R.	1967	Factors affecting the response of small watersheds to precipitation in humid areas	In Sopper, W.E. and Lull, H.W., editors, Forest hydrology, New York: Pergamon Press, 275—90				√			
Wolman, M.G.	1967	A cycle of sedimentation and erosion in urban river channels	Geografiska Annaler 49A: 385–395			√				√
Vita-Finzi, C.	1969	The Mediterranean valleys: geological changes in historical times	Cambridge: Cambridge University Press			√				
Chorley, R.J., Kennedy, B.A.	1971	Physical Geography: A systems approach	London: Prentice Hall		√	√	√			√
Wilson, I.G.	1971	Desert sandflow basins and a model for the development of ergs	The Geographical Journal 137, 180—99			√				
Rothlisberger, H.	1972	Water pressure in intra- and subglacial channels	Journal of Glaciology 11: 177-203.				√	√		
Gregory, K.J., Walling, D.E.	1973	Drainage basin, form and process: a geomorphological approach	London: Arnold			√	√			
Manley, G.	1974	Central England temperatures: monthly means 1659-1973	Quarterly Journal of the Royal Meteorological Society 100: 389-405		√					
Manabe, S., Wetherald, R.T.	1975	The effects of doubling CO2 concentration on the climate of a general circulation model	Journal of Atmospheric Sciences 32: 3-15		√					
Shroder, J.F.	1975	Dendrogeomorphological analysis of mass movement	Proceedings of the Association of American Geographers 7: 222–226	√			√			
Dury, G.H.	1976	Discharge prediction, present and former, from channel dimensions	Journal of Hydrology 30: 219-245				√	√		
Sugden, D.E. and John, B.S.	1976	Glaciers and landscape: a geomorphological approach	London: Arnold			√		√		
Knox, J.C.	1977	Human impacts on Wisconsin stream channels	Annals of the Association of American Geographers 67: 224–244			√	√			√
Kirkby, M.J. (ed.)	1978	Hillslope hydrology	Chichester: Wiley				√			
Brunsden, D., Thornes, J.B.	1979	Landscape sensitivity and change	Transactions of the Institute of British Geographers, 4: 463-484			√				
Schumm, S.A.	1979	Geomorphic thresholds: The concept and its applications	Transactions of the Institute of British Geographers 4: 485–515			√				

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E.,	1980	The river continuum concept	Canadian Journal of Fisheries and Aquatic Sciences 37: 130-137.	√		√				
Büdel, J.	1982	Climatic geomorphology	Princeton: Princeton University Press		√	√				
Trimble, S.W.	1983	A sediment budget for Coon Creek basin in the driftless area, Wisconsin, 1983-1977	American Journal of Science 283: 454-474			√				√
Walling, D.E.	1983	The sediment delivery problem	Journal of Hydrology 65: 209-237			√	√			
Wasson, R.J., Hyde, R.	1983	Factors determining desert dune type	Nature 304: 337—339			√				
Osterkamp W.R., Hupp C.R.	1984	Geomorphic and vegetative characteristics along three northern Virginia streams	Bulletin of the Geological Society of America 95: 1093–1101	√		√				
Petts, G.E.	1984	Impounded Rivers: Perspectives for Ecological Management	Chichester: Wiley	√		√	√			√
Thornes, J.B.	1985	The ecology of erosion	Geography 70: 222—35	√		√	√			
Grove, J.M.	1988	The Little Ice Age	London: Routledge		√			√		
McFadden, L.D., Knuepfer, P.L.K.	1990	Soil geomorphology – the linkage of pedology and surficial processes	Earth-Science Reviews 97: 257–272			√			√	

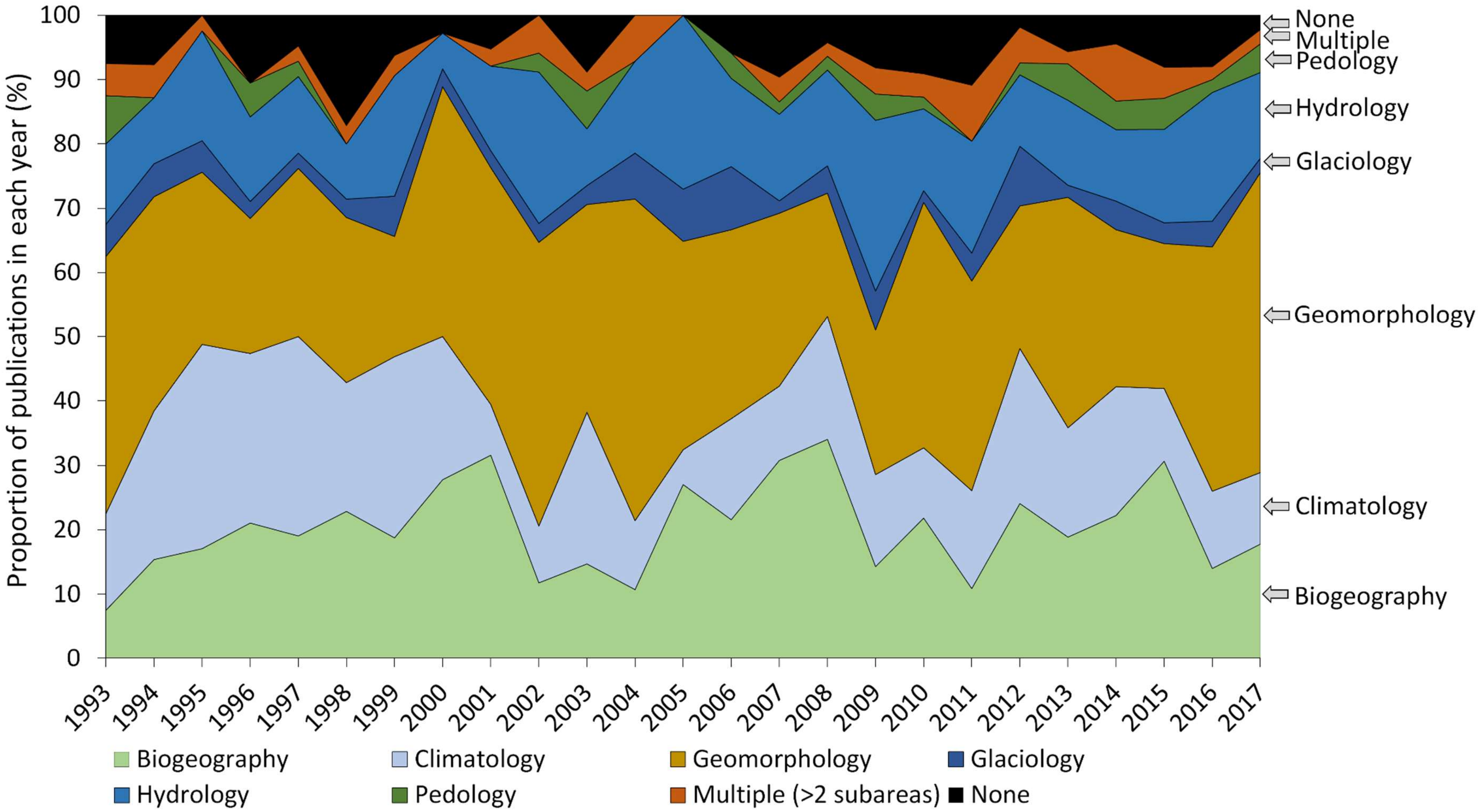

Figure 1 The percentage of publications concerned with different sub-areas of physical geography. (In each year publications were allocated to up to two (occasionally three) subareas or to the categories multiple or none - the percentages relate to total occurrence of these categories, which is slightly greater than simply to the total number of individual publications analysed).

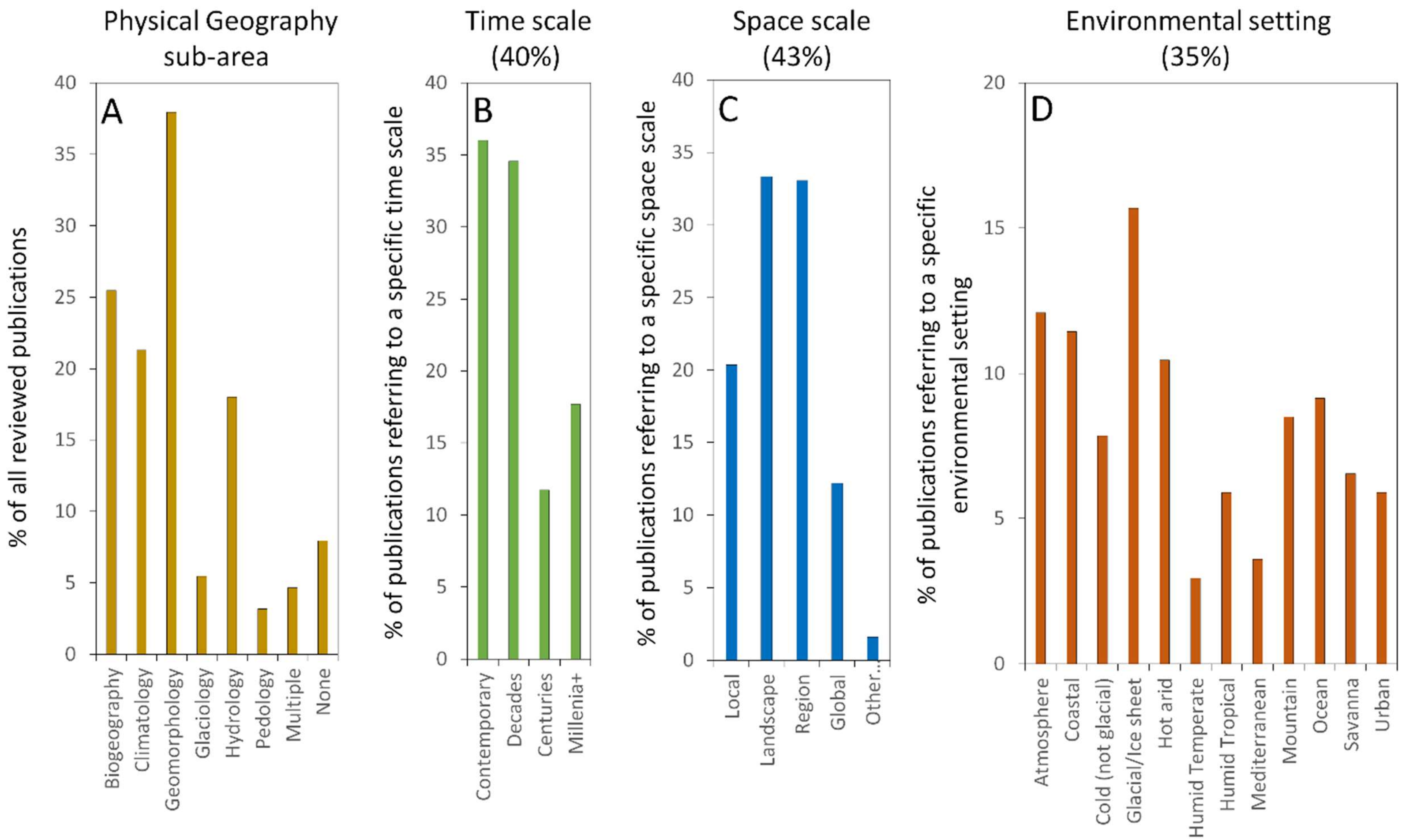

Figure 2 A. The proportion of all publications falling into different subareas of physical geography (Note that the percentages add up to more than 100% because each publication may relate to more than one subarea). The proportions of papers addressing different B. timescales, C. space scales, and D. environmental settings. (The percentages noted at the top of each of graphs B, C and D refer to the proportion of all surveyed publications that clearly indicate time or space scales or environmental setting and the graphs then specify the proportion of publications within those groups that refer to the individual scales or settings. Note that the percentages in graph B add up to more than 100% because each publication may relate to up to two timescales)

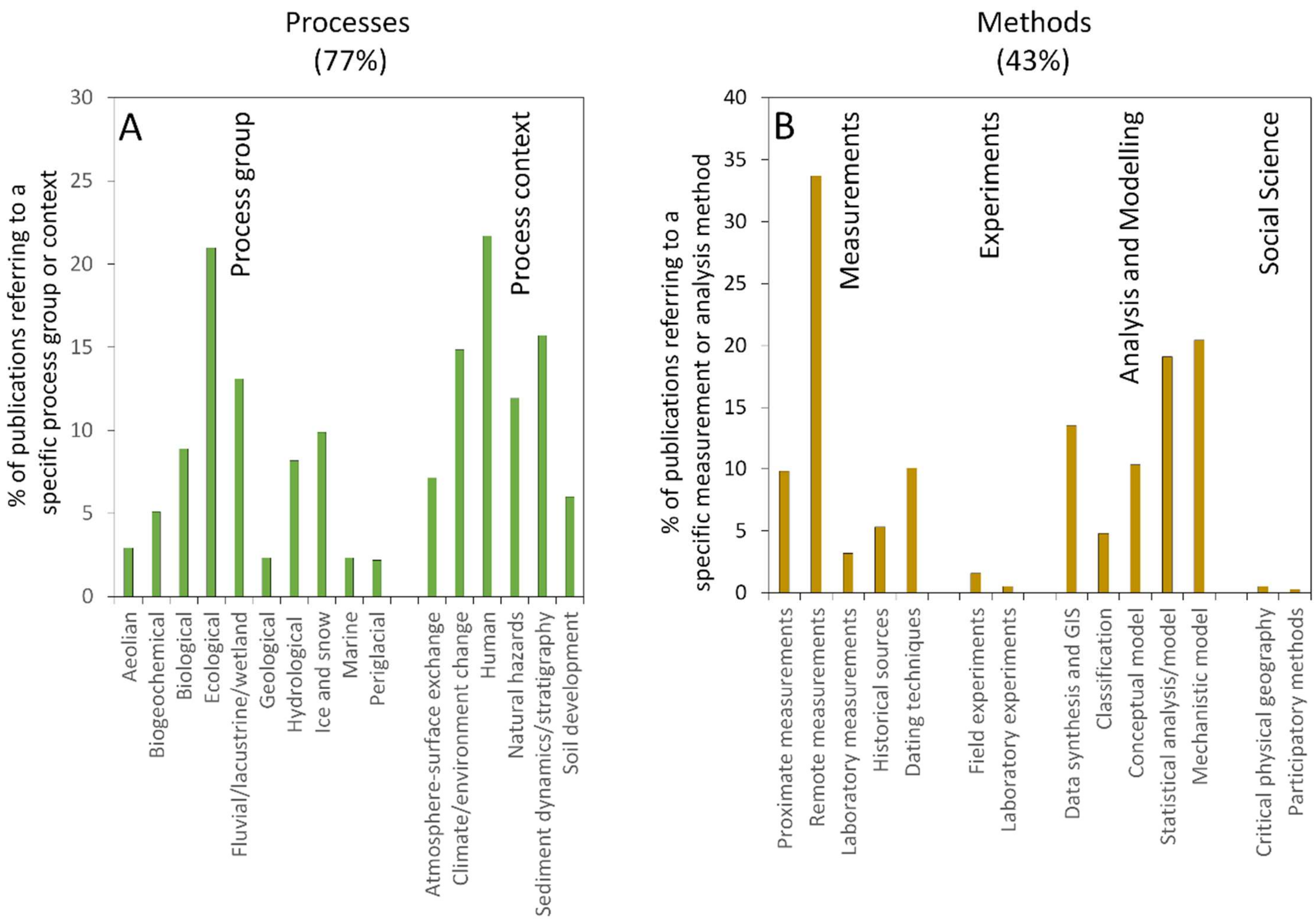

Figure 3 A. Process groups / contexts considered and B. Methods reviewed by the analysed publications. The percentages noted at the top of each of graph refer to the overall proportion of publications that clearly indicate process groups/contexts or methods and the graphs analyse only those publications, providing overall proportions, although bars are grouped to aid visual interpretation. (Note that the percentages in graphs A and B add up to more than 100% because each publication may relate to up to two categories).