Impact of Climate Change on Land, Water and Ecosystem Quality in Polar and Mountainous Regions: Gaps in our knowledge

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Abstract

Nowhere are the effects of climate change more visible than in polar and mountainous regions. To initiate the Interregional Technical Co-operation Project INT/5/153 (2014-18) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions (funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture), we built a database containing 769 of the most significant journal papers on the effects of climate change in polar and mountainous regions between 2000-2014 (up until the Fifth IPCC Assessment). Using the number of paper citations per year (CPY) we derive the top fifty most cited journal papers published in the 15-year period. Analysis of the focus of these 'top fifty' papers is compared to the IPCC Fifth Assessment (AR5) Report (IPCC, 2013) and the full database. Five categories emerged, and by combining the number of papers in each category with the average CPY for the category, research on the impacts of climate change on terrestrial ecosystems (E) in polar and mountainous regions dominated, research on the impact on water resources (W) was second, the impact on people's livelihood (P) third, with ice and snow (I) fourth and landscape (L) fifth. Landscape (L), in our view, appears to be under researched and is presumably included in the IPCC Terrestrial Ecosystems category. We propose that policy makers should note this under-representation of high impact research into landscape processes (erosion and deposition processes), which needs to be addressed in future.

Key words: citation alanysis; literature review; climate change impacts; polar regions; mountainous regions; livelihood adaptation; soil-water-ecosystem quality

Introduction

Modern climate change has been described as ‘the defining human development challenge of the 21st century’ (United Nations Intellectual History Project, 2011). Model projections suggest that global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 for all Representative Concentration Pathways adopted by the Intergovernmental Panel Climate Change (except RCP2.6) (IPCC, 2013). Indeed, average global warming in the period 1990-2100 is expected to be between 1.1 and 6.4°C depending on the global release of greenhouse gas emissions (Kohler and Maselli, 2009). This warming will not be uniform, but in general will be greater over land and in high latitudes.

Nowhere are its effects already more visible than in the polar and mountainous regions. Climate change is progressing at a rate several times the global average in Western Antarctica for example. The Antarctic Peninsula region has experienced a rise of ca. 3°C for surface air temperature over the last 50 years (Bromwich *et al.,* 2013), and 87% of 244 glaciers along the west coast of the Antarctic Peninsula (AP) have retreated in the last fifty years (Cook & Vaughan, 2010). Higher elevation sites in the Rocky Mountains have experienced a threefold increase in warming compared to the global average during the last few decades (Kohler and Maselli, 2009). In the European Alps regional climate projections indicate warming of about 1.5 times the global average, with greater warming in summer (FAO, 2015). Precipitation is projected to decrease in summer and in an annual average, and to increase in winter, although Giorgi *et al.* (2016) used an ensemble of global climate model simulations to conclude that while broad-scale summer precipitation reduction is projected, the regional models simulate an increase in precipitation over the high Alpine elevations that is not present in the global simulations. This finding challenges the picture of a ubiquitous decrease of summer precipitation over the Alps found in coarse-scale projections. General warming is predicted to result in an upward shift of the glacier equilibrium line by between 60 to 140 m per degreeC temperature increase (Oerlemans, 2003), along with a substantial glacier retreat during the 21st century. The duration of snow cover is expected to decrease by several weeks for each degree C of warming at middle elevations in the Alpine region.

The 1992 United Nations Framework Convention on Climate Change recognized that “developing countries with fragile mountainous ecosystems are particularly vulnerable to the adverse effects of climate change” (United Nations, 1992). Agenda 21 (Chapter 13) identified the need to generate and strengthen knowledge about the ecology and sustainable development of mountain ecosystems, and the Rio+20 United Nations Conference on Sustainable Development in 2012 called for long-term vision and a holistic approach to sustainable mountain development.

Examining the impacts of climate change in Antarctic and Arctic landscapes can be particularly useful for a better understanding of the future impacts of climate change on landscape dynamics (including land degradation and resulting changes in land, water and ecosystem quality) in mountainous regions across the world. Mountains cover around 25% of the global land surface and are home to 10% of the world’s population. An estimated 40% of mountain populations are located in developing countries and nearly 300 million mountain people are food insecure with half suffering from chronic hunger (Kohler and Maselli, 2009). Furthermore, it is estimated that mountains provide freshwater to half of the world’s population. Climate change will affect the availability of water, and combined with increasing temperatures can make farming communities in some countries, such as those in the Andes in South America or in the Himalaya, shift to higher altitudes, often in more fragile ecosystems, where slopes which are no longer supported by glaciers become unstable leading to landslides, mass movements and related hazards which can result in severe land degradation and undermine food security. Zhang *et al*. (1997) working on the North Slope, Alaska, reported that the thickness of the active layer increased from the Arctic coast to the foothills of the Brooks Range and is directly proportional to summer air temperatures and thawing index. Increasing air temperature will therefore seem to result in continuously or seasonally frozen soils releasing more greenhouse gases into the atmosphere, but the magnitude of this effect remains highly uncertain (UNEP/WGMS, 2008).

The United Nations Environment Programme (UNEP) reports indicate the need for getting better access to existing data, better knowledge of the data quality and the generation of new data in a manner that allows data sharing among researchers (UNEP, 1992).

Aims and objectives

This paper aims to identify and discuss the top fifty most cited (and therefore, arguably the highest impact) journal papers published in the 15-year period 2000-2014 which relate to the issue of climate change impact in polar and mountainous regions. Analysis of the focus of these ‘top fifty’ papers will be compared to the IPCC Fifth Assessment (AR5) Report (IPCC, 2013) and a wider database of 800 journal articles and key reports. The intention is that this analysis will highlight where we have gaps in our knowledge and therefore serve to help policy makers and funders of research to plug these knowledge gaps.

This analysis was carried out in the frame of Interregional Technical Co-operation Project INT/5/153 (2014-18) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions, which is organized and funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The project involved scientists from twenty-three countries representing thirteen benchmark research sites (Fig. 1) designed to assess the impact of climate change on land-water-ecosystem quality in polar and mountainous regions. The overall objective of the project is to improve the understanding of the impact of climate change on fragile polar and mountainous ecosystems at the local and global scale for their better management and conservation.

Figure 1: World map to show Benchmark sites of the INT 5153 project

The project expects to have the following outcomes: (1) improved understanding of the impact of climate change on the cryosphere, and its effects on land-water-ecosystem quality at local and global scale in polar and mountainous ecosystems, (2) recommendations for improvement of regional policies for soil and agricultural water management, conservation, and environmental protection in polar and mountainous regions.

Methods

Developing a literature database

It was decided in the planning stage for the INT5153 project that a database should be developed which should:

1. Be easily accessible to, and updatable by, all members of the project, project partners and managers,
2. Focus on peer reviewed scientific literature
3. Be searchable by key words, date, journal and benchmark site,
4. Focus on research produced in the last TWO IPCC Assessment Reports (Four and Five), i.e. since the year 2000.
5. Perform a gap analysis that should prepare the ground for the scientific approach and training and highlight where we have gaps in our knowledge and therefore serve to help policy makers and funders of research to plug these knowledge gaps.

After some discussion with a core team, it was decided that Microsoft EXCEL would meet the criteria as a widely available platform in which to build the database. The following stages were completed to populate the database:

1. Google Scholar (http://scholar.google.co.uk/) was used and search terms were input as follows: "climate change *King George Island*" etc with the benchmark site (*italics*) changed for each of 13 searches (one search for each of the benchmarks sites shown in Fig. 1). Between 10-13 key journal papers were then selected from the first 20 search hits and entered into the database. This generated around 150 entries.
2. All project members were invited by email to contribute additional literature relating to their benchmark sites by email. This generated approximately 200 further entries for the database.

3. Following the First Project Co-ordination meeting in Vienna in June 2014, scientists representing benchmark sites forwarded further scientific papers arising from research undertaken at/around their benchmark site/research station and a further 248 papers were subsequently added to the database bringing the total number of entries to around 550.
4. Next the top 35 academic journals which most frequently appeared in the database were assigned an impact factor (Garfield, 1999).
5. The journal impact factor was then used to calculate the proportion of the remaining entries to the database which were to come from each of the top 35 journals.
6. Each of the 35 journals was searched in turn, normally using the Science Direct online database or google scholar to find references relevant to the project using the terms: ‘climate’, ‘change’, ‘impact’, ‘polar’, ‘mountainous’, ‘regions’.
7. It was intended to stop searching when the database reached 800, but uncovering new papers became increasingly difficult and searching stopped at 769 entries.
8. The number of citations for each paper (found from Google Scholar) was entered into a new column in the database. The number of citations the paper had was then divided by the age (the number of years it had been published prior to 2014) of the publication to derive the average number of citations per year, CPY.
9. The database entries were then ranked from highest to lowest based on the CPY.
10. The top fifty ranked papers were then selected for content analysis and compared with findings from IPCC and the full database

Findings

Summary of database content

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The distribution of database entries by year of publication (Fig. 2) shows that all years 2000-2014 were represented in the database, though the higher numbers in the second half of the period correspond with the statement made by IPCC (2014) “The number of scientific publications available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation” (IPCC, 2014).

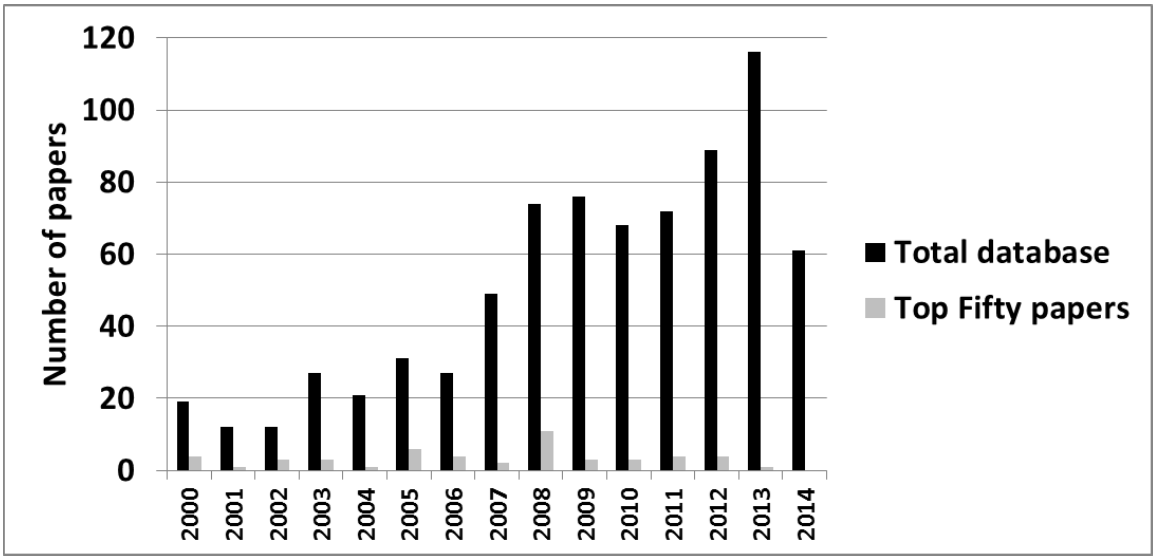

Fig. 2: Distribution of database entries by year of publication.

The fifty papers with the highest average citations per year (hereafter simply referred to as the ‘top fifty’) are also drawn from all years except 2014. That none of the top fifty papers were published in 2014 (and only one in 2013) may reflect the fact that these top papers need some time to gather citations and therefore work their way into this top fifty. Typical journal paper publication times are 6-18 months so it is unlikely that a high impact paper published in 2014 would have had enough time to be cited by other authors and therefore gain enough citations to reach this top fifty.

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The 769 entries in the database included 31 reports, 31 book chapters, 18 Conference/Symposium Proceedings, 21 web news articles, 5 books and 191 different journals. (Table 1).

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Table 1: Titles of journals (with number of entries) used in database

Journal	No	Journal	No	Journal	No	Journal	No
Acta Bot. Boreal.-Occident. Sin	1	Earth System Science Data	2	International Journal of Water Resources Development	1	Polar Science	1
Acta Ecologica Sinica	1	Ecological Applications	1	Journal of Agronomy and Crop Science	1	Polish Polar Research	1
Acta Geológica Hispánica	1	Ecological Economics	1	Journal of African Earth Sciences	1	POLISH JOURNAL OF ECOLOGY	1
Acta PedologicaS Inica	1	Ecology	2	Journal of Arid Environments	2	Problems of Arctic and Antarctic	3
Acta Societatis Botanicorum Poloniae	2	Ecological Monographs	1	Journal of Asian Earth Sciences	1	Proceedings of the National Academy of Sciences	1
Advances in Agronomy	1	Ecology and Society	1	Journal of Biogeography	2	Progress in Development Studies	1
Advances in Climate Research	1	Ecology Letters	2	Journal of China University of Geosciences	2	Progress in Physical Geography	1
Advances in Ecological Research	13	Ecosystems	1	Journal of Climate	1	Quaternary International	9
Advances in Geosciences	3	Emotion, Space & Society	1	Journal of Climatology	1	Quaternary Research	1
Agricultural and Forest Meteorology	1	Energy Policy	2	Journal of Food, Agriculture & Environment	1	Quaternary Science	1
Agricultural Systems	1	Engineering Geology	1	Journal of Environmental	2	Quaternary Science Reviews	13

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				Radioactivity			
Agriculture, Ecosystems and Environment	1	Environmental and Resource Economics	1	Journal of Environmental Management	1	Regional Environmental Change	1
Agricultural Water Management	1	Environmental Conservation	1	Journal of Geophysical Research	9	Radiation and Environmental Biophysics	1
Ambio	7	Environmental Development	1	Journal of Glaciology	14	Remote Sensing Letters	1
American Scientist	1	Environmental Management	1	Journal of Glaciology and Geocryology	2	Remote Sensing of the Environment	16
Annals of Botany	1	Environmental Pollution	1	Journal of Historical Geography	1	Renewable and Sustainable Energy Reviews	1
Annals of Glaciology	8	Environmental Research Letters	4	Journal of Hydrology	12	Report	30
Annals of the Association of American Geographers	3	Environmental Science and Policy	5	Journal of Hydrometeorology	1	Report in Spanish	1
Annals of Tourism Research	1	EOS	2	Journal of Integrated Disaster Risk Management	1	Resources Science	1
Antarctic Science	1	Forest Ecology and Management	3	Journal of Mountain Science	4	Resource and environment in the Yangtse basin	1
Applied Soil Ecology	2	Forest Policy and Economics	1	Journal of Paleolimnology	1	Reviews of Geophysics	1
Arctic, Antarctic, and Alpine Research	12	Forestry Studies in China	2	Journal of Plant Nutrition and Soil Science	1	Revista Brasileira de Geomorfologia	3
Atmospheric Chemistry & Physics	1	Freshwater Biology	1	Journal of Quaternary Science	2	Revista de la Asociación Geológica Argentina	1
Austrian Journal of Earth Sciences	2	Fungal Ecology	1	Landslides	2	Scandinavian Journal of Forest Research	2
Biodiversity	1	Geochimica et Cosmochimica Acta	1	Marine Geology	1	**Science**	44

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Biogeochemistry	1	Geoderma	3	Microbes and Infection	1	Science China Earth Sciences	1
Biogeosciences	2	Geografiska Annaler: Series A, Physical Geography	5	Mountain Research and Development	6	Science of the Total Environment	4
Bioscience	3	Geographica Helvetica	1	Mycorrhiza	1	Silva Fennica	1
Book	5	Geology	1	Natural Hazards	5	Soil Biology and Biogeochemistry	2
Book chapter	31	Geology Today	1	Natural Hazards and Earth System Sciences	3	Soil Science Society of America Journal	1
Canadian Water Resources Journal	1	Geomorphology	16	**Nature**	34	Soils	1
Catena	2	Geophysical Research Abstracts	2	**Nature Climate Change**	28	Spanish Journal of Agricultural Research	1
CECNet	1	Geophysical Research Letters	7	**Nature Geoscience**	35	State of Antarctic environment Quarterly Bulletin	2
Central Asia and the Caucasus	1	Global and Planetary Change	21	Norsk Geografisk Tidsskrift	1	Surveys in Geophysics	1
Chinese Journal of Plant Ecology	1	Global Biogeochemical Cycles	2	Oceanography-Oceanography Society	1	Sustainable Development	1
Climate Change	11	Global Change Biology	15	Organic Geochemistry	1	Technological Forecasting and Social Change	1
Climate Dynamics	1	Global climate change and cold regions ecosystems	1	PAGES News	1	Tellus	3
Climate of the Past	1	Global Ecology and Biogeography	2	Palaeogeography, Palaeoclimatology, Palaeoecology	7	The Holocene	1
Conference/Symposium Proceedings	18	Global Environmental Change	10	Permafrost and Periglacial Processes	4	The Lancet	1
Cryosphere	12	Hydrological Processes	15	Perspectives in Plant Ecology, Evolution and Systematics	1	Theoretical and Applied Climatology	3

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Current Biology	1	Hydrological Sciences Journal	2	Pesquisa Antártica Brasileira	1	The Review of Economics and Statistics	2
Current Opinon in Environmental Sustainability	2	Hydrology and Earth System Sciences	6	PhD Thesis	3	Tourism Management	1
Danish Journal of Geography	1	IAHS Symposuin Proceedings	2	Philosophical Transactions of the Royal Society A	1	Transactions American Geophysical Union	2
Discussion paper	2	Ice and snow	2	Photogrammetric Engineering and Remote Sensing	1	Tree Physiology	1
Earth and Planetary Science Letters	2	International Journal of Climatology	2	Plant and Soil	1	Trees	1
Earth Surface Processes and Landforms	2	International Journal of Environmental Protection	1	PloS one	5	Water International	1
Earth-Science Reviews	15	International Journal of Remote Sensing	1	Polar biology	5	Water Science and Technology	1
		International Journal of Sustainable Society	1	Polar Geography	1	Zeitschrift für Geomorphologie	1

Science, Nature Geoscience and Nature were the top three of the most popular journals with entries of three or more (Fig. 3).

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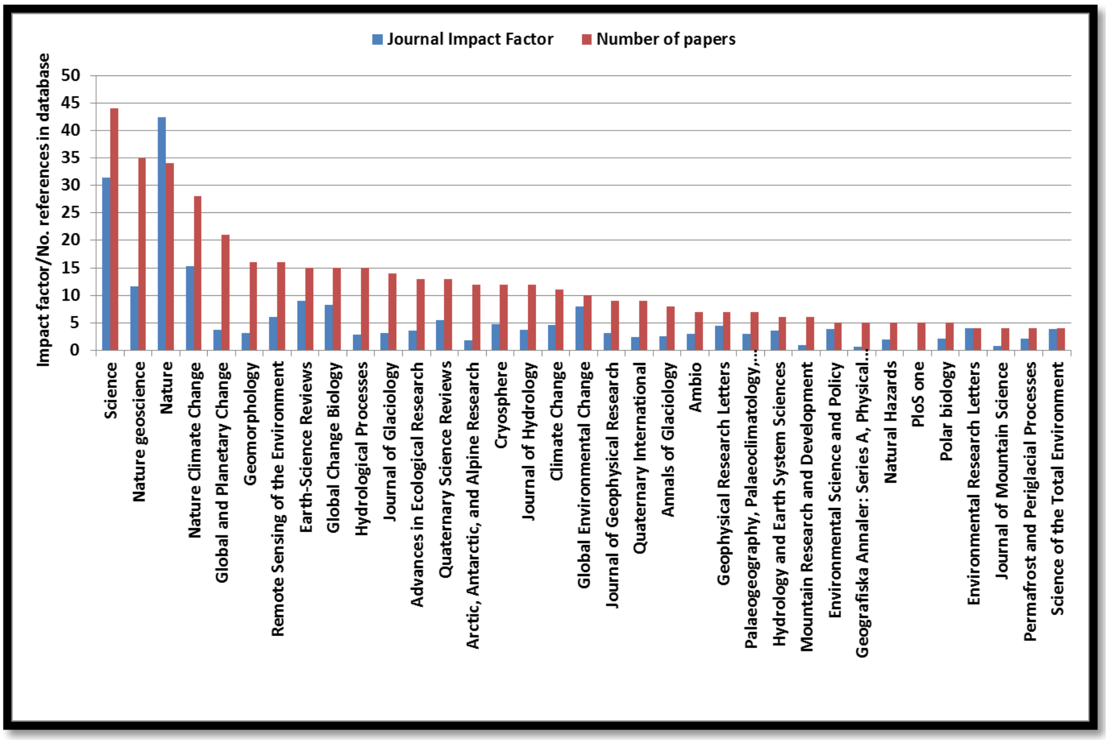

Fig. 3: Most popular journals in database (with three or more entries)

The top 35 journals (based on impact factor) and the number of entries in the database for each journal is given in Table 2.

Table 2: List of the top 35 highest impact academic journals used to search for material relevant to climate change impacts in polar and mountainous regions to supplement the papers provided by benchmark site scientists.

		30/05/2014	IMPACT FACTOR	% of total	Search target	02/09/2014
	Journal Title	Number	13-Aug-14	Impact	Number	Number
1	Science	8	31.477	15	44	44
2	Nature Geoscience	1	11.668	5	16	35
3	Nature	10	42.351	20	60	34
4	Nature Climate Change	3	15.295	7	22	28
5	Global and Planetary Change	16	3.707	2	5	21
6	Geomorphology	6	3.167	1	4	16
7	Remote Sensing of the Environment	5	6.065	3	9	16
8	Earth-Science Reviews	2	8.95	4	13	15
9	Global Change Biology	1	8.22			15
10	Hydrological Processes	7	2.81	1	4	15
11	Journal of Glaciology	9	3.213	2	5	14
12	Advances in Ecological Research	4	3.59	2	5	13
13	Quaternary Science Reviews	5	5.463	3	8	13
14	Arctic, Antarctic, and Alpine Research	8	1.78	1	3	12
15	Cryosphere	2	4.684	2	7	12
16	Journal of Hydrology	3	3.678	2	5	12
17	Climate Change	3	4.622	2	6	11
18	Global Environmental Change	1	8.05			10
19	Journal of Geophysical Research	5	3.174	1	4	9
20	Quaternary International	2	2.446	1	3	9
21	Annals of Glaciology	9	2.524	1	4	8
22	Ambio	7	2.973	1	4	7
23	Geophysical Research Letters	5	4.456	2	6	7
24	Palaeogeography, Palaeoclimatology, Palaeoecology	5	3.035	1	4	7
25	Hydrology and Earth System Sciences	5	3.59	2	5	6
26	Mountain Research and Development	3	0.989	0	1	6
27	Environmental Science and Policy	1	3.948	2	6	5
28	Geografiska Annaler: Series A, Physical Geography	5	0.659	0	1	5

29	Natural Hazards	4	1.958	1	3	5
30	PloS one	1				5
31	Polar biology	2	2.071	1	3	5
32	Environmental Research Letters	3	4.09	2	6	4
33	Journal of Mountain Science	2	0.763	0	1	4
34	Permafrost and Periglacial Processes	1	2.177	1	3	4
35	Science of the Total Environment	2	3.906	2	5	4

There was a significant relationship between the number of journal references added to the database and the impact factor, i.e. the higher the journal impact factor, the more papers from that journal that were searched and added (Fig. 4). This approach was adopted so that the database contained a significant proportion (164 or 21.3%) of high impact research papers drawn from the top 35 impact factor journals shown in Table 2 which are not specifically linked to benchmark sites for the INT 5153 project. This, we believe, strengthened the validity of the database and added to the 512 entries which are specifically linked to the benchmark sites or regions chosen for this project.

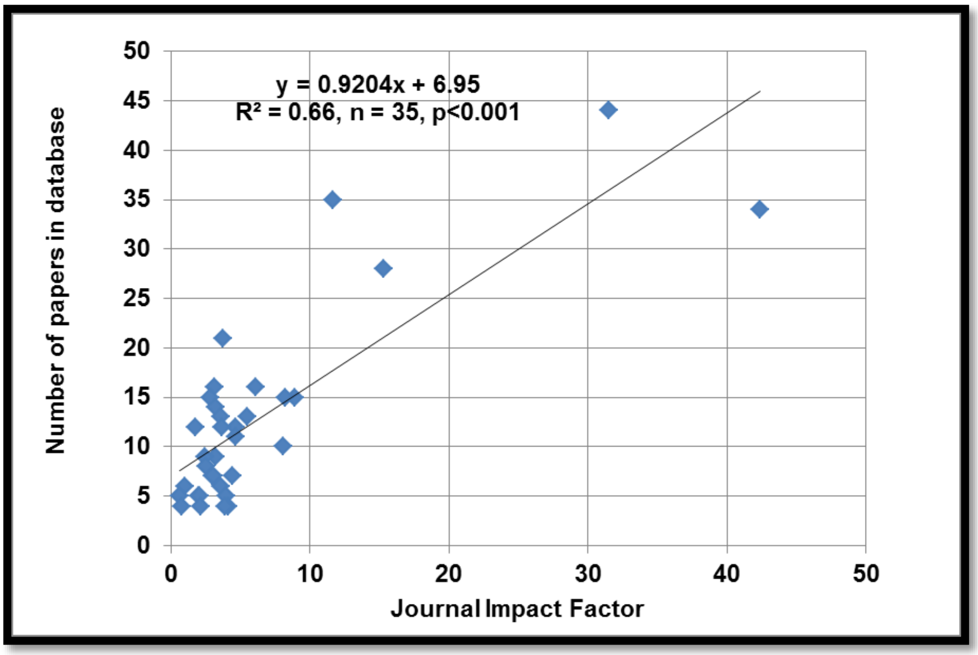

Fig. 4: Relationship between number of papers and journal impact factor.

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The key words (up to three) which were entered next to each entry in the database (Table 3). In total, 1113 key words were entered next to database entries and these were assigned to five categories based on emerging themes (Maykut and Morehouse, 1994) which are colour coded in Table 3. Keywords associated with glacier/recession/melt/mass balance had the highest count of 208.

Table 3: Keywords (with number of entries) used in database. Note that colour coding key at top of table corresponds to categories.

KEY WORDS & THEIR CLASSIFICATION

COLOUR KEY		
Impacts on Snow, Glaciers, Ice Caps and Ice Sheets	Impacts on Livelihoods: Agriculture, Food, Water Security and Hydropower	Impacts on Landscape, Geomorphology and Slope Stability
Impacts on Terrestrial Ecosystems: Soil, Biodiversity, Greenhouse gases and Feedback systems	Impacts on Water and Water Resources	Non-coloured = Not assigned

Keywords	TOTAL				
Abrupt climate change	1	Feedback	6	Quinoa	6
Accimatisation capacity	1	Food security/production	5	Rainfall	3
Adaptation	33	Frost	6	Range shifts	3
Afforestation	1	Fungi	1	Rockfall	4
African drought	0	Geomorphology	1	Remote sensing	7
Aerial photos	3	GHGs/emissions	6	Respiration	3
Airborne laser	1	Glacier/recession/melt/mass balance	5	Risk	1
Agriculture/Crops/Biofuels	24	Glacial lakes/lakes/proglacial lakes	208	River discharge/runoff	20
Agroforestry	1	GLOF/jokulhaulp	14	Rock glacier	2
Animals/Fauna	6	Governance	22	Sea level/rise	4
Annual Production/Biomass	2	Grassland/grazing	1	Sediment	1
Arctic tundra/fen	8	Hazard management	4	Ski industry	2
Biodiversity	5	HEP	10	Slope failure	6
Biogeochemical cycling/response	3	Human/adaptaton/response	5	Snow cover/melt/avalanche/pack	31
Biomass burning/wildfire	3	Hydrology/irrigation	10	Socio-economic/vulnerability/limts	34
Black carbon	3	Ice sheet/mass/core	46	Soil carbon/respiration/moisture/sequester	29
Carbon/cycle/CO2	49	Isotope	13	Soil erosion	1
Catastrophic soil erosion	1	Lake/Lake ice	5	Species	3
Climate /change/extremes/hazard	78	Land/land-use/cover	16	Sub-marine	1
Crops/yields	8	Landslide/mass movement/slope failure	9	Suspended sediment	5
Crustal uplift	4	Management	26	Technology	1
Cryosphere	5	Mapping	2	Terrestrial ecosystem/cabon cycle	4
Cultural dimension	1	Methane/emissions/flux	57	Tropical	6
Damage costs/disease/disaster	4	Nutrients/	13	Thawing	6
Dating	1	Organic matter/carbon	4	Trees/tree-line/tree rings	13
Dams	1	Organisations	7	Vegetation	12
Debris flow	4	Palaeoclimate	7	Villages	1
Dendrochronology	1	Peat/decomposition	7	Vulnerability	3
Dust	1	Periglacial/permafrost/active layer	2	Water resources/water	48
Early warning system (landslide)	1	Phosphorus	52	Weathering	1
Ecology/Ecosystems	3	Pine beetle	2	Weeds	1
Ecomonics/impacts	25	Plant/ecology/herbivore interaction	5	Wetlands	2
Energy/budgets/HEP	8	Planation	1	TOTAL	1113
Forests	8	Policy/political	9		

Looking at the years when journals papers in the database were published, there is a tendency towards a normal distribution, but it is skewed towards the second half of the period searched which indicates that the number of research papers concerned with the impacts of climate change on land-water-ecosystem quality is on the increase. After checking and cleaning the database (for example, some repeat entries were noted and removed) there was a final total of 720 entries which included 615 journal papers (from 191 different journals), 31 reports, 31 book chapters, 19 Conference/Symposium Proceedings, 18 web news articles, 6 books.

Four of the five categories which emerged from the analysis of the 1015 key words corresponded to the four used by IPCC (2014): Snow and Ice (termed Ice in this study, abbreviated to I); Rivers and Lakes (termed Water in this study, abbreviated to W); Terrestrial Ecosystems (termed Ecosystems in this study, abbreviated to E) and Food Production & Livelihoods (termed People in this study, abbreviated to P) plus a new Landscape category (abbreviated to L). The five categories into which the keywords were grouped, the number of keywords associated with each group, and the percentage of the papers in the database which were in each group are given in Table 4.

Table 4: Number of key words and % of total in five categories (rank order)

	TOTAL KEYWORDS	%
Impacts on Snow & Ice (I) glacier, glacier recession, glacier melt/ablation, glacier mass balance, glacier mapping/inventory; ice sheet, ice mass, ice core; periglacial, permafrost, active layer; cryosphere; snow cover, snow melt, snow pack, snow avalanche	366	36.1
Impacts on Terrestrial Ecosystems (E) agriculture, crops, yields, biofuels; animals, fauna; biomass, biodiversity; biogeochemical cycling/response; biomass burning, wildfires; black carbon, carbon, carbon cycle, carbon dioxide; ecology, ecosystem; forests, feedback; greenhouse gases; emissions; grassland, grazing; land use, land cover; methane, methane emissions/flux; nutrients, organic matter; peat decomposition; plants, herbivores; species; range shift; respiration; sequestration; trees, vegetation, weeds; wetland/fen	260	25.6
Impacts on Water (W) water, water resources; lakes, glacial lakes, proglacial lakes, lake ice; hydrology; irrigation; rainfall; river discharge; runoff; sea level	173	17.0
Impacts on People's Livelihoods (P)	146	14.4

acclimatisation capacity, adaptation; cultural dimension; damage costs, disease, disaster; economic impacts; energy, hydropower; food security, food production; governance; hazard management; risk, human adaptation, human response; migration; management, organisations, policy, political; ski industry, tourism; socio-economic; technology; vulnerability		
Impacts on Landscape (L) Soil erosion; debris flow; geomorphology; landslide, mass movement, slope failure, rockfall; sediment, suspended sediment; weathering	70	6.9
TOTAL	1015	100

Using the five categories in Table 4, all database entries were assigned to one or more of these, leaving 721 entries which had citations assigned. On closer inspection it was found that 58 of the journal paper entries were only concerned with climate change and not the impact of climate change on polar and mountainous regions. These papers were assigned the category C (for Climate) and thereafter removed from the analysis, leaving 663 journal articles remaining. However, sometimes research papers were concerned with more than one category. For example, if the paper was concerned with glacier recession (I) and changes in runoff (W), then it was assigned IW (eg. a study of glacial lake outburst floods). 157 of the journal papers were assigned two categories and 13 were assigned three categories. When the total number of papers in each category was calculated, a paper with two categories, such as IW, would be assigned 0.5 to I and 0.5 to W. For three categories such as IEW, then each category would be assigned 0.33. Table 5 shows the results for all papers in database (columns 2-3) and top 50 only (columns 6-7) and the last row shows the ranking of the five categories. Columns 4 and 8 in Table 5 show the average number of citations per year (CPY) for each category and columns 5 and 9 gives the product of the number of papers multiplied by the average CPY. This measure, we believe, gives the most robust weighting for each category. The final row in Table 5 summarises the ranks with E > W > P > I > L being the order for all papers in the database and for the Top Fifty.

Table 5: Comparison of all papers in database vs top 50 only.

Category	All Papers in Database				Top 50 papers			
	No. papers in database	% of papers in database	Average CPY*	No. papers x Ave CPY*	No. papers in top 50	% of papers in top 50	Average CPY*	No. papers x Ave CPY*
I	213	33.7	31	6609	3.5	7.0	315.3	1104
E	194	30.6	121	23457	28.5	57.0	376.6	10733
W	97	15.3	103	9968	7.5	15.0	282.6	2120
P	74	11.6	94	6915	10.0	20.0	287.5	2875
L	55	8.7	40	2238	0.5	1.0	49.9	25
TOT	633	100.0			50	100		
RANKS	I > E > W > P > L		E > W > P > I > L		E > P > W > I > L		E > W > P > I > L	

* CPY = citations per year.

Most papers published in the last 15 years concerned with the impact of climate change on polar and mountainous regions are classified as I. There are 213 papers in this category which represents 33.7% of the total. There are 194 papers in the E category which represents 30.6% of the total. The third category, the impact of climate change on the water (rivers and lakes) (W) contained 97 papers (15.3% of the total). The fourth category, climate change impacts on people and livelihoods (P) contained 74 papers (11.6% of the total). The fifth category, landscape (L) contained 55 papers (8.7% of the total).

These distributions can be compared with the IPCC (2014) confidence levels of knowledge in each of the first four categories (I-E-W-P) (see Fig. 5). The fifth category (L) has been

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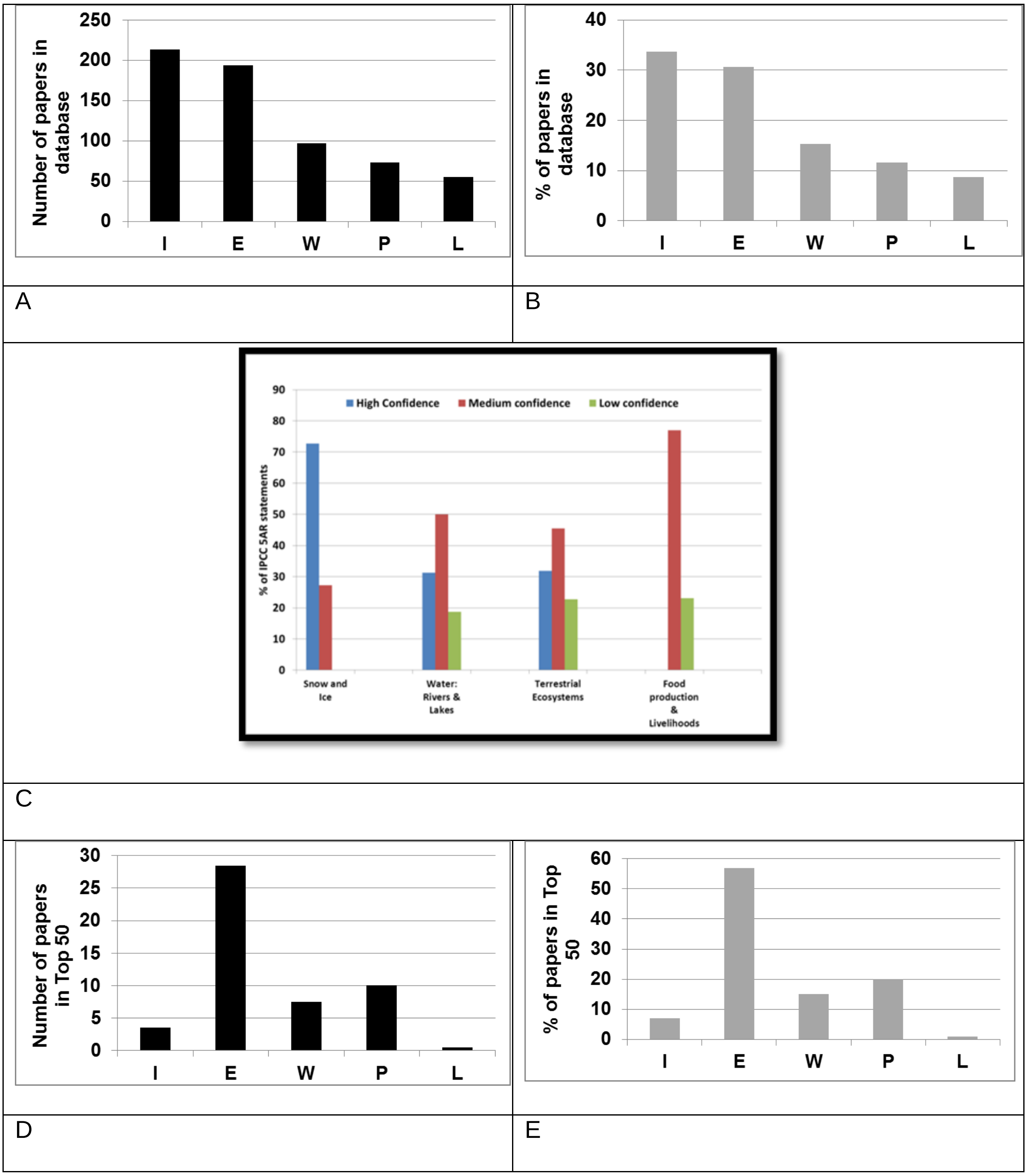
created by us through the key word analysis (Table 3). However, the IPCC (2014) deals with the levels of confidence that the 5AR has in making statements about the impact of climate change on snow and ice (I); rivers and lakes (W); terrestrial ecosystems (E) and food production/livelihoods (P). Figs. 5A and B show the number and percentage of the research papers in these categories, and includes the fifth category, landscape (L) which, in our view, appears to be under researched and is presumably included in the IPCC Terrestrial Ecosystems category. We feel that policy makers should note this under-representation of research, or at least high impact research, on landscape processes which we discuss in more detail later.

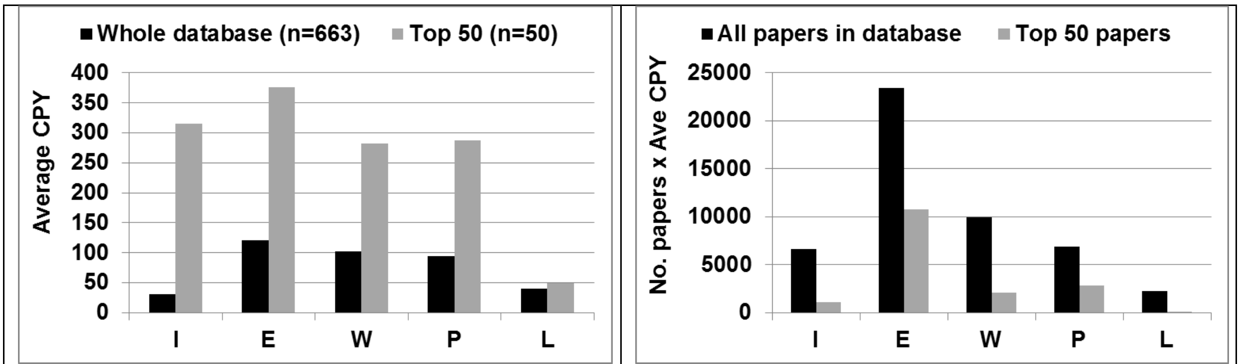
Fig. 5. A: Number of papers in whole database in the five categories (n = 633), B: Percentages of papers in whole database in the five categories, C: Confidence levels in statements made by IPCC (2014) in four areas which are being impacted by climate change (IPCC, 2014), D: Number of papers in Top 50 (by CPY) in the five categories (n = 50), E: Percentages of papers in Top 50 (by CPY) in the five categories



Figs. 5D and E present the distribution for just the Top Fifty - the fifty papers in the database with this highest number of citations per year (CPY). There is a clear mis-match between the nature of the research coming from the larger database (of 663 papers) and those in the Top Fifty. The rank order has changed from I > E > W > P > L to E > P > W > I > L. In other words, the number of research papers in I reaching the top 50 has declined hugely, from 33.7 in the whole database to just 7.0% in the top 50 while research on terrestrial ecosystems (E) has increased from 30.6% in the whole database to 57.0% in the top 50. P has moved up from fourth to second rank of the five categories (increased from 11.6% in the whole database to 20.0% in the top 50), and water (W) has remained in third place (changed 15.3% in the whole database to 15.0% in the top 50). Landscape research (L) remains in fifth place (decreased from 8.7% in the whole database to just 1.0% in the top 50).

The average citations per year (CPY) for whole database and the Top 50 papers and the number of papers x average citations per year (CPY) for whole database and the Top 50 papers is shown in Fig. 6.

Figure 6. A: Average citations per year (CPY) for whole database and the Top 50 papers, B: Number of papers x average citations per year (CPY) for whole database and the Top 50 papers.



A	B

Fig. 6A indicates that when considering citations per year (CPY) as a measure of impact or importance to the scientific community, the rank order of categories is E > W > P > L > I for the whole database but becomes E > I > P > W > L for the top 50 papers. It would therefore seem sensible to combine the number of papers in each category by the average citations per year (CPY) for the category. This results in Fig. 6B which gives the rank order for the whole database as E>W>P>I>L and the ranks for the top 50 papers are the same.

So, to conclude this section, research concerned with the impacts of climate change on terrestrial ecosystems (E) in polar and mountainous regions dominates, with papers on the impact on water resources (W) being second and a very close third the impact on people's livelihood (P), with I fourth and L fifth. The distribution for the Top Fifty highest impact papers closely mirrors the distribution of papers in the larger database of 663 journal papers. Therefore, a more detailed examination of the research undertaken in the Top Fifty highest impact papers is proposed for the discussion of this paper.

In order to assess the changes over the 15 year (2000-14) period, it was decided to split the database into three five year time periods: 2000-04; 2005-09; 2010-14 (Fig. 7), which shows how the number of papers (Fig. 7A) and the percentage or papers (Fig. 7B) in each of the five categories changed through the three time periods. Fig. 7A shows that the number of papers increased in each category from 2000-04 to 2005-09 and again to 2010-14.

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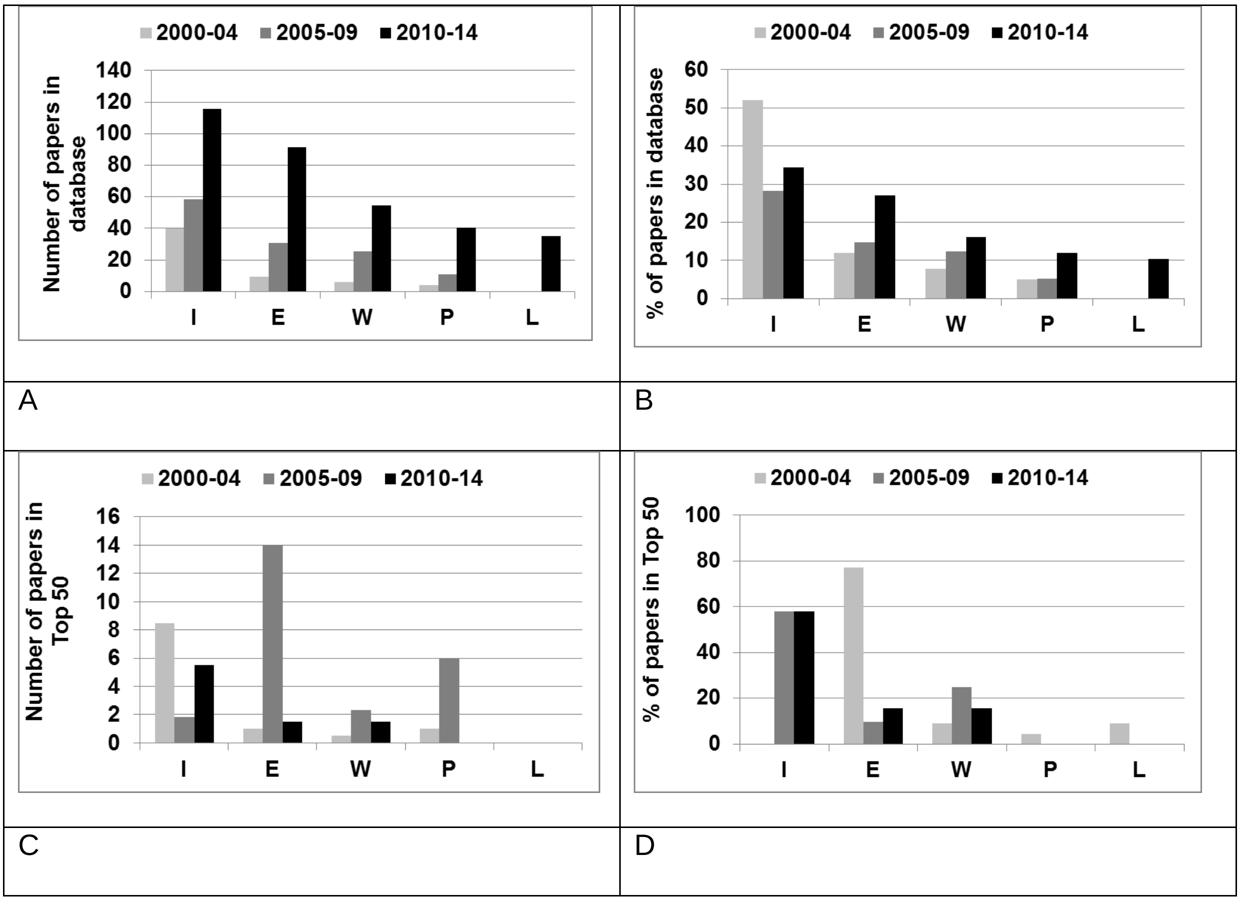
Figure 7. A: Changes in the number of papers in each category over time (n = 663), B: Changes in the percentage of papers in each category over time (n = 663), C: Changes in the number of papers in each category over time in Top 50 (n = 50), D: Changes in the percentage of papers in each category over time in Top 50 (n = 50).



On examining the Top 50 papers (Figs. 7C and D), it is difficult to see any obvious pattern over the 15 year period.

Discussion

Content of the Top Fifty Highest Impact papers

A closer examination of these Top Fifty papers was made. The topic of the research was noted and Table 6 shows the most popular research topics in the Top Fifty papers.

Table 6: Most popular research topics in the Top Fifty papers

Category	Topic	No. of papers	Authors, Year and Impact Rank
E	Species distribution change, biodiversity	10	Parmesan & Yohe, 2003 (2); Walther *et al.*, 2002 (3); Sala *et al.,* 2000 (5); Chen *et al.,* 2011 (10); Dawson *et al.,* 2011 (27); Lenoir *et al.*, 2008 (36); Schröter *et al.,* 2005 (40); Stenseth *et al.,* 2002 (41); Davis & Shaw, 2001 (44); Post *et al*., 2009 (48).
EP/P/W	Agriculture and food production, water resources	6	Lal, 2004 (24); Lobell *et al.,* 2011 (12); Lobell *et al.,* 2008 (16); Piao *et al*., 2010 (31); Shindell *et al.,* 2012 (28); Asseng et al., 2013 (46).
E/EP	Greenhouse gases, feedback mechanisms	6	Searchinger *et al.,* 2008 (1); Fargione *et al.,* 2008 (4); Westerling *et al.,* 2006 (6); Cox *et al.,* 2000 (13); Bonan, 2008 (9); Cramer et al., 2001 (34).
E/EP	Soil and forest carbon, carbon cycle	6	Davidson & Janssens, 2006 (7); Lal, 2004 (8); Kurz *et al.,* 2008 (22); Van der Werf *et al*., 2009 (39); Donato *et al.,* 2011 (42); Bond-Lamberty & Thomson, 2010 (45).
P	Human health, social limits, adaptation	5	Adger et al., 2009 (18); McMichael *et al.,* 2006 (23); Patz *et al.,* 2005 (26); Shindell *et al.,* 2012 (28); Adger *et al*., 2003 (49).
W	Water resources	4	Barnet *et al*., 2005 (19); Piao *et al*., 2010 (31); Vörösmarty *et al*., 2000 (25); Immerzeel *et al*., 2010 (30).
I	Himalayan, Antarctic, Patagonian glaciers	2	Bolch *et al.,* 2012 (37); Schaefer *et al.,* 2013 (11).

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W/IW	Sea level rise	2	Jacob *et al*., 2012 (33); Nicholls & Cazenave, 2010 (29).
E/EP	Land use change, forest management	1	Canadell & Raupach, 2008 (50).
E	Primary production	1	Nemani *et al.,* 2003 (21).
E	Disease risk	1	Harvell *et al*., 2002 (32).
E	Deforestation	1	Malhi *et al.,* 2008 (35).
EW	Soil moisture	1	Seneviratne et al., 2010 (20).
I	Black carbon	1	Ramanathan & Carmichael, 2008 (15).
IE	Permafrost thaw	1	Hinzman et al., 2005 (47).
IE	Carbon dioxide sinks	1	Le Quéré *et al*., 2009 (14).
P	Sustainable Development-equity	1	Smit & Pilifosova, 2003 (43).
P	Economics of climate change	1	Weitzman, 2009 (17).
LW	Sediment flux to oceans	1	Syvitski *et al*., 2006 (38).

The most researched topics in the Top Fifty papers were concerned with the impact of climate change on species distribution and biodiversity and 10 of the papers (20%) addressed this. Six papers (12%) addressed the impact of climate change on agriculture and food production, six papers (12%) were about greenhouse gases/feedback mechanisms and a further 6 papers (12%) were on the subject of soil and forest carbon/carbon cycle. Five papers (10%) addressed human health/social limits/adaptation. Next, water resources had four papers (8%) dealing with that topic.

Two papers (6%) were on the impacts on Himalayan, Antarctic and Patagonian glaciers; Two papers (10%) were concerned with sea level rise and the remaining 11 papers (2% each) were each concerned with a range of topics as outlined in Table 6. Inevitably, there is scope for some overlap, where for example, the paper by Searchinger *et al.,* (2008) found that the use of US croplands for biofuels increases greenhouse gases through emissions from land-use change, and so bridges the agriculture and greenhouse gas topics.

Ecosystems

The highest impact paper found in this whole study concerned with ecosystems was by Searchinger *et al.* (2008) (Table 7), who reported that the use of US croplands for biofuels increases greenhouse gases through emissions from land use change.

Table 7: Top Ten Highest Cited Papers in the Ecosystems (E) Category

Rank	Publication	Year	Journal	Impact Factor	No. citations	Age of paper	No. Citations per year (CPY)
1	Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., ... & Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319(5867), 1238-1240.	2008	Science	34.4	3255	7	465.0
2	Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. Nature, 421(6918), 37-42.	2003	Nature	42.351	5230	12	435.8
3	Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J., ... & Bairlein, F. (2002). Ecological responses to recent climate change. Nature, 416(6879), 389-395.	2002	Nature	42.351	5249	13	403.8
4	Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. Science, 319(5867), 1235-1238.	2008	Science	34.4	2785	7	397.9
5	Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., ... & Wall, D. H. (2000). Global biodiversity scenarios for the year 2100. science, 287(5459), 1770-1774.	2000	Science	34.4	4657	15	310.5
6	Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. science, 313(5789), 940-943.	2006	Science	34.4	2338	9	259.8
7	Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440(7081), 165-173.	2006	Nature	42.351	2228	9	247.6
8	Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. science, 304(5677), 1623-1627.	2004	Science	34.4	2512	11	228.4

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9	Bonan, G. B. (2008). Forests and climate change: forcings, feedbacks, and the climate benefits of forests. science, 320(5882), 1444-1449.	2008	Science	34.4	1442	7	206.0
10	Chen, I. C., Hill, J. K., Ohlemüller, R., Roy, D. B., & Thomas, C. D. (2011). Rapid range shifts of species associated with high levels of climate warming. Science, 333(6045), 1024-1026.	2011	Science	34.4	781	4	195.3

Fargione *et al.* (2008) pointed out that converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States created a “biofuel carbon debt”. Parmesan & Yohe (2003) reported that attributing the causes of recent biological trends to climate change is complicated because non-climatic influences dominate local, short-term biological changes. Walther *et al.* (2002) claimed that there was ample evidence of the ecological impacts of recent climate change, from polar terrestrial to tropical marine environments and their review exposed a coherent pattern of ecological change across systems. Sala *et al.* (2000) claimed that scenarios of changes in biodiversity for the year 2100 could be developed based on scenarios of changes in atmospheric carbon dioxide, climate, vegetation, and land use and the known sensitivity of biodiversity to these changes. Davidson & Janssens’ (2006) key paper points out that despite much research, a consensus has not yet emerged on the temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Lal (2004) estimated that the carbon sink capacity of the world's agricultural and degraded soils is 50 to 66% of the historic carbon loss of 42 to 78 gigatons of carbon.

Westerling *et al.* (2006) showed that large wildfire activity in the US increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. Bonan (2008) illustrated how the world's forests influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition. Chen *et al.,* 2011 identified rapid shifts of species associated with high levels of climate warming.

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People and Livelihoods

Investments aimed at improving agricultural adaptation to climate change inevitably favour some crops and regions over others. Lobell *et al.* (2008) were ranked highest in the Top Ten Highest Cited Papers in the People and Livelihoods (P) Category (Table 8). They performed an analysis of climate risks for crops in 12 food-insecure regions to identify adaptation priorities, based on statistical crop models and climate projections for 2030 from 20 general circulation models.

Table 8: Top Ten Highest Cited Papers in the People and Livelihoods (P) Category

Rank	**Publication**	**Year**	**Journal**	**Impact Factor**	**No. citations**	**Age of paper**	**No. Citations per year (CPY)**
1	Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. Science, 319(5863), 607-610.	2008	Science	34.4	1195	7	170.7
2	Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics, 91(1), 1-19.	2009	The Review of Economics and Statistics	2.718	971	6	161.8
3	Adger, W. N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D. R., ... & Wreford, A. (2009). Are there social limits to adaptation to climate change?. Climatic change, 93(3-4), 335-354.	2009	Climate Change	4.622	959	6	159.8
4	McMichael, A. J., Woodruff, R. E., & Hales, S. (2006). Climate change and human health: present and future risks. The Lancet, 367(9513), 859-869.	2006	The Lancet	45.217	1153	9	128.1
5	Patz, J. A., Campbell-Lendrum, D., Holloway, T., & Foley, J. A. (2005). Impact of regional climate change on human health. Nature, 438(7066), 310-317.	2005	Nature	42.351	1261	10	126.1
6	Shindell, D., Kuylenstierna, J. C., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., ... & Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security.	2012	Science	34.4	364	3	121.3

	Science, 335(6065), 183-189.						
7	Smit, B., & Pilifosova, O. (2003). Adaptation to climate change in the context of sustainable development and equity. Sustainable Development, 8(9), 9.	2003	Sustainable Development	1.242	1051	12	87.6
8	Adger, W. N., Huq, S., Brown, K., Conway, D., & Hulme, M. (2003). Adaptation to climate change in the developing world. Progress in development studies, 3(3), 179-195.	2003	Progress in Development Studies	0.789	874	12	72.8
9	Hsiang, S. M., Meng, K. C., & Cane, M. A. (2011). Civil conflicts are associated with the global climate. Nature, 476(7361), 438-441.	2011	Nature	42.351	243	4	60.8
10	Adger, W. N., Barnett, J., Brown, K., Marshall, N., & O'Brien, K. (2013). Cultural dimensions of climate change impacts and adaptation. Nature Climate Change, 3(2), 112-117.	2013	Nature Climate Change	15.295	109	2	54.5

Weitzman (2009) analyzed the implications of structural uncertainty for the economics of low-probability, high-impact catastrophes. Adger *et al.* (2009) contended that limits to adaptation are endogenous to society and hence contingent on ethics, knowledge, attitudes to risk and culture. McMichael *et al.* (2006) summarised the epidemiological evidence of how climate variations and trends affect various health outcomes. Patz *et al*. (2005) argued that many prevalent human diseases are linked to climate fluctuations, from cardiovascular mortality and respiratory illnesses due to heatwaves, to altered transmission of infectious diseases and malnutrition from crop failures.

Shindell *et al.* (2012) considered ~400 emission control measures to reduce pollutants by using current technology and experience. Smit & Pilifosova (2003) examined adaptation to climate change in the context of sustainable development and equity, while Adger *et al.* (2003) reported on adaptation to climate change in the developing world. Hsiang *et al.* (2011) wrote about how civil conflicts are associated with the global climate. Adger *et al.* (2013) analysed new research across the social sciences to show that climate change

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threatens cultural dimensions of lives and livelihoods that include the material and lived aspects of culture, identity, community cohesion and sense of place.

Water

Barnett *et al.* (2005) were ranked highest in the Top Ten Highest Cited Papers in the Water (W) Category (Table 9). They reported on the potential impacts of a warming climate on water availability in snow-dominated regions.

Table 9: Top Ten Highest Cited Papers in the Water (W) Category

Rank	**Publication**	**Year**	**Journal**	**Impact Factor**	**No. citations**	**Age of paper**	**No. Citations per year (CPY)**
1	Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438(7066), 303-309.	2005	Nature	42.351	1506	10	150.6
2	Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. Science, 289(5477), 284-288.	2000	Science	34.4	1894	15	126.3
3	Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. Science, 328(5985), 1517-1520.	2010	Science	34.4	605	5	121.0
4	Immerzeel, W. W., Van Beek, L. P., & Bierkens, M. F. (2010). Climate change will affect the Asian water towers. Science, 328(5984), 1382-1385.	2010	Science	34.4	586	5	117.2
5	Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., ... & Fang, J. (2010). The impacts of climate change on water resources and agriculture in China. Nature, 467(7311), 43-51.	2010	Nature	42.351	577	5	115.4
6	Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., ... & Treidel, H. (2013). Ground water and climate change. Nature Climate Change, 3(4), 322-329.	2013	Nature Climate Change	15.295	129	2	64.5

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7	García-Ruiz, J. M., López-Moreno, J. I., Vicente-Serrano, S. M., Lasanta–Martínez, T., & Beguería, S. (2011). Mediterranean water resources in a global change scenario. Earth-Science Reviews, 105(3), 121-139.	2011	Earth Science Reviews	8.95	227	4	56.8
8	Fischer, G., Tubiello, F. N., Van Velthuizen, H., & Wiberg, D. A. (2007). Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. Technological Forecasting and Social Change, 74(7), 1083-1107.	2007	Technological Forecasting and Social Change	1.274	255	8	31.9
9	Wang, G. Y., Shen, Y. P., Su, H. C., WANG, J., MAO, W. Y., GAO, Q. Z., & WANG, S. D. (2008). Runoff changes in Aksu River Basin during 1956–2006 and their impacts on water availability for Tarim River. Journal of Glaciology and Geocryology, 30(4), 562-568.	2008	Journal of Glaciology and Geocryology	0	168	7	24.0
10	Petra Schmocker-Fackel, Felix Naef, More frequent flooding? Changes in flood frequency in Switzerland since 1850, Journal of Hydrology, 381 (1–2), 1-8.	2010	Journal of Hydrology	3.678	73	5	14.6

Vörösmarty et al. (2000) examined global water resources and their vulnerability from climate change and population growth. Nicholls & Cazenave (2010) claimed that global sea level rise through the 20th century will almost certainly accelerate through the 21st century and beyond because of global warming, but its magnitude remains uncertain. Immerzeel *et al.* (2010) investigated how climate change will affect the Asian water towers - more than 1.4 billion people depend on water from the Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers. Piao *et al.* (2010) examined the impacts of climate change on water resources and agriculture in China, the world’s most populous country and a major emitter of greenhouse gases. Taylor *et al.* (2013) studied groundwater and climate change, groundwater being the world's largest distributed store of fresh water, which plays a central part in sustaining ecosystems and enabling human adaptation to climate variability and change. García-Ruiz *et al.* (2011) reported that Mediterranean areas of both southern Europe and North Africa were subject to dramatic changes that would affect the sustainability, quantity, quality, and management of water resources. Fischer *et al.* (2007) investigated potential changes in global and regional agricultural water demand for irrigation within a new socio-economic scenario with and without climate change. Wang *et al.* (2008) analysed runoff changes in Aksu River Basin during 1956–2006 and their impacts on water availability for Tarim River. Schmocker-Fackel & Naef (2010) examined changes in flood frequency in Switzerland since 1850 and postulated on more frequent flooding.

Ice and Snow

Schaefer *et al*. (2013) were ranked highest in the Top Ten Highest Cited Papers in the Ice and Snow (I) Category (Table 10). They generated digital elevation models of the Northern and Southern Patagonia Icefields of South America from the 2000 Shuttle Radar Topography Mission. Which were compared with earlier cartography to estimate the volume change of the largest 63 glaciers. Table 10 shows the Top Ten Highest Cited Papers in the Ice and Snow (I) Category

Table 10: Top Ten Highest Cited Papers in the Ice and Snow (I) Category

Rank	Publication	Year	Journal	Impact Factor	No. citations	Age of paper	No. Citations per year (CPY)
1	Schaefer, M., H. Machgut, M. Falvey and G. Casassa. 2013. Modeling the mass balance of the Northern Patagonia Icefield. Journal of Geophysical Research, Earth Surface, 118(1-18), doi:10.1002/jgrf.20038.	2013	Journal of Geophysical Research	3.426	368	2	184.0
2	Ramanathan, V., & Carmichael, G. (2008). Global and regional climate changes due to black carbon. Nature Geoscience, 1(4), 221-227.	2008	Nature Geoscience	11.668	1222	7	174.6
3	Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M. & Wagnon, P. (2013): Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. The Cryosphere 7:	2013	Cryosphere	5.51	105	2	52.5

	81-102						
4	Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B. G., & Bradley, R. S. (2008). Climate change and tropical Andean glaciers: Past, present and future. Earth-Science Reviews, 89(3), 79-96.	2008	Earth Science Reviews		296	7	42.3
5	Rignot, E., Koppes, M., & Velicogna, I. (2010). Rapid submarine melting of the calving faces of West Greenland glaciers. Nature Geoscience, 3(3), 187-191.	2010	Nature Geoscie nce	11.6 68	187	5	37.4
6	Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., ... & Vonder Mühll, D. (2009). Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses. Earth-Science Reviews, 92(3), 117-171.	2009	Earth Science Reviews	8.95	221	6	36.8
7	Brown, R., and P. Mote, 2009: The response of Northern Hemisphere snow cover to a changing climate. J. Clim., doi:10.1175/2008JCLI2665.1, 2124–2145.	2009	Internati onal Journal of Climatol ogy	3.51 7	186	6	31.0
8	Christiansen, H. H., Etzelmüller, B., Isaksen, K., Juliussen, H., Farbrot, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, J., Hjort, J., Holmlund, P., Sannel, A.B.K., Sigsgaard, C., Åkerman, H. J., Foged, N., Blikra, L. H., Pernosky, M. A. and Ødegård, R. S. 2010: The thermal state of permafrost in the Nordic area during the international polar year 2007-2009. Permafrost and Periglacial Processes 21:156-181.	2010	Permafr ost and Periglaci al Process es	2.11 9	131	5	26.2
9	Moholdt, G., Christopher Nuth, Jon Ove Hagen, Jack Kohler, Recent elevation changes of Svalbard glaciers derived from ICES at laser altimetry, Remote Sensing of Environment, 114 (11), 2756-2767.	2010	Remote Sensing of Environ ment	6.06 5	117	5	23.4
10	Racoviteanu, A. E., Arnaud, Y., Williams, M. W., & Ordonez, J. (2008). Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. Journal of Glaciology, 54(186), 499-510.	2008	Journal of Glaciolo gy	3.21 3	150	7	21.4

Ramanathan & Carmichael (2008) reported on global and regional climate changes due to the deposition of black carbon which darkens snow and ice surfaces and can contribute to melting, in particular of Arctic sea ice. Rabatel *et al.* (2013) reported that the glacier retreat in the tropical Andes over the last three decades was unprecedented since the maximum extension of the Little Ice Age (LIA, mid-17th–early 18th century). Vuille *et al.* (2008) reviewed climate change and tropical Andean glaciers. Rignot *et al.* (2010) observed widespread glacier acceleration in Greenland which they associated with the thinning of the lower reaches of the glaciers as they terminate in the ocean.

Harris *et al.* (2009) presented a review of the changing state of European permafrost within a spatial zone that included the continuous high latitude arctic permafrost of Svalbard and the discontinuous high altitude mountain permafrost of Iceland, Fennoscandia and the Alps. Brown and Mote (2009) examined the response of Northern Hemisphere snow cover to a changing climate, and Christiansen *et al.* (2010) reported on the thermal state of permafrost in the Nordic area during the international polar year 2007-2009.

Moholdt *et al.* (2010) tested three methods for estimating 2003–2008 elevation changes of Svalbard glaciers from multi-temporal ICESat laser altimetry, and Racoviteanu e*t al.* (2008) measured decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing.

Landscape

Syvitski *et al.* (2005) were ranked highest in the Top Ten Highest Cited Papers in the Landscape (L) Category (Table 11). They provided global estimates of the seasonal flux of sediment, on a river-by-river basis, under modern and pre-human conditions.

Table 11: Top Ten Highest Cited Papers in the Landscape (L) Category

Rank	**Publication**	**Year**	**Journal**	**Impact Factor**	**No. citations**	**Age of paper**	**No. Citations per year (CPY)**

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1	Syvitski, J. P., Vörösmarty, C. J., Kettner, A. J., & Green, P. (2005). Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science, 308(5720), 376-380.	2005	Science	34.4	998	10	99.8
2	Guzzetti, F., Mondini, A. C., Cardinali, M., Fiorucci, F., Santangelo, M., & Chang, K. T. (2012). Landslide inventory maps: New tools for an old problem. Earth-Science Reviews, 112(1), 42-66.	2012	Earth Science Reviews	8.95	195	3	65.0
3	Prospero, J. M., & Lamb, P. J. (2003). African droughts and dust transport to the Caribbean: Climate change implications. Science, 302(5647), 1024-1027.	2003	Science	34.4	593	12	49.4
4	Huggel, C., Clague, J. J., & Korup, O. (2012). Is climate change responsible for changing landslide activity in high mountains? Earth Surface Processes and Landforms, 37(1), 77-91.	2012	Earth Surface Processes and Landforms	2.845	58	3	19.3
5	Stoffel, M., & Huggel, C. (2012). Effects of climate change on mass movements in mountain environments. Progress in Physical Geography, 36(3), 421-439.	2012	Progress in Physical Geography	2.612	58	3	19.3
6	Crozier M.J. (2010) Deciphering the effect of climate change on landslide activity: A review. Geomorphology 124 (3–4): 364–369.	2010	Geomorphology	3.167	79	5	15.8
7	Kääb, A., Frauenfelder, R., and Roer, I. (2007). On the response of rock glacier creep to surface temperature increase. Global and Planetary Change, 56(1), 172-187.	2007	Global and Planetary Change	3.155	119	8	14.9
8	Huggel, C., Salzmann, N, Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W., Larsen, C., Schneider, D., and Wessels, R. (2010): Recent and future warm extreme events and high-mountain slope failures. Philosophical Transactions of the Royal Society A, 368, 2435-2459.	2010	Philosophical Transactions of the Royal Society A	2.147	68	5	13.6
9	Huggel, C. (2009). Recent extreme slope failures in glacial environments: effects of thermal perturbation. Quaternary Science Reviews, 28(11), 1119-1130.	2009	Quaternary Science Reviews	4.572	74	6	12.3
10	Mabit, L., M. Benmansour, J.M. Abril, D.E. Walling, K. Meusburger, A.R. Iurian, C. Bernard, S. Tarján, P.N. Owens, W.H. Blake, C. Alewell. (2014) Fallout 210Pb as a soil and sediment tracer in catchment sediment budget investigations: A review, Earth-Science Reviews, Available online 3 July 2014, ISSN 0012-8252, http://dx.doi.org/10.1016/j.earscirev.2014.0	2014	Earth Science Reviews	8.95	12	1	12.0

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	6.007.						

Prospero & Lamb (2003) reported that great quantities of African dust are carried over large areas of the Atlantic and to the Caribbean during much of the year. Landslides are present in all continents, and play an important role in the evolution of landscapes. Climate change, manifested by an increase in mean, minimum, and maximum temperatures and by more intense rainstorms, is becoming more evident in many regions. An important consequence of these changes may be an increase in landslides in high mountains. They also represent a serious hazard in many areas of the world. Despite their importance, Guzzetti *et al.* (2012) estimated that landslide maps covered less than 1% of the slopes in the landmasses, and systematic information on the type, abundance, and distribution of landslides was lacking. Huggel *et al.* (2012) analyzed a series of catastrophic slope failures that occurred in the mountains of Europe, the Americas, and the Caucasus since the end of the 1990s and distinguished between rock and ice avalanches, debris flows from de-glaciated areas, and landslides that involved dynamic interactions with glacial and river processes. Stoffel & Huggel (2012) reported that changes in mass-movement activity could hardly be detected in observational records. They documented the role of climate variability and change on mass-movement processes in mountains through the description and analysis of selected, recent mass movements where effects of global warming and the occurrence of heavy precipitation were thought to have contributed to, or triggered, events. Crozier (2010) identified the mechanisms by which climate can induce land sliding and examined the manner in which these mechanisms may respond to changes in a range of climatic parameters. Using a one-dimensional thermo-mechanically coupled numerical model, Kääb *et al.* (2007) simulated the potential response of rock glacier creep to a change in surface temperature.

Huggel *et al.* (2010) reported on recent and future warm extreme events and high-mountain slope failures, and Huggel (2009) described exceptional slope failures in high-mountain, glacial environments: the 2002 Kolka–Karmadon rock–ice avalanche in the Caucasus, a series of ice–rock avalanches on Iliamna Volcano, Alaska, the 2005 Mt. Steller rock–ice avalanche in Alaska, and ice and rock avalanches at Monte Rosa, Italy in 2005 and 2007.

Increasing anthropogenic pressures coupled with climate change impacts on natural resources have promoted a quest for innovative tracing techniques for understanding soil redistribution processes and assessing the environmental status of soil resources. Mabit *et al.* (2014) provided a comprehensive evaluation and discussion of the various applications of 210Pbex as a tracer in terrestrial and aquatic environments, with particular emphasis on catchment sediment budget investigations. Their paper summarizes the state-of-the-art related to the use of this tracer, the main assumptions, the requirements (including the need for accurate analytical measurements and for parallel validation), and the limitations which must be recognised when using this fallout radionuclide as a soil and sediment tracer.

Conclusion

In this paper we describe the building and subsequent analysis of a database containing 769 of the most significant journal papers on the effects of climate change in polar and mountainous regions between 2000-2014 (up until the Fifth IPCC Assessment). Using the number of paper citations per year to derive the top fifty most cited journal papers published in the 15-year period, an analysis of the topic of these ‘top fifty’ papers is compared to the IPCC Fifth Assessment (AR5) Report (IPCC, 2013) and the wider database of 769 entries.

By number, most papers published in the last 15 years concerned with the impact of climate change on polar and mountainous regions are classified as I (ice and snow). There are 213 papers in this category which represents 33.7% of the total. There are 194 papers in the E (terrestrial ecosystems) category which represents 30.6% of the total. The third category, the impact of climate change on the water (rivers and lakes) (W) contained 97 papers

(15.3% of the total). The fourth category, climate change impacts on people and livelihoods (P) contained 74 papers (11.6% of the total). The fifth category, landscape (L) contained 55 papers (8.7% of the total). So, in rank order by numbers of papers the categories are: I > E > W > P > L. These distributions can be compared with the IPCC (2014) confidence levels of knowledge in each of the first four categories (I >E>W>P also), the fifth category (L) has been created by us through the key word analysis. However, the IPCC (2014) deals with the levels of confidence that the 5AR has in making statements about the impact of climate change on snow and ice (I); rivers and lakes (W); terrestrial ecosystems (E) and food production/livelihoods (P).

However, when only considering the Top 50 papers (ranked by highest number of citations per year, CPY), there is a clear mis-match between the nature of the research coming from the larger database (of 663 papers) and those in the Top Fifty. The rank order has changed from I > E > W > P > L in the whole database to E > P > W > I > L in the Top 50. In other words, the number of research papers in I reaching the top 50 has declined hugely, from 33.7 in the whole database to just 7.0% in the top 50 while research on terrestrial ecosystems (E) has increased from 30.6% in the whole database to 57.0% in the top 50. P has moved up from fourth to second rank of the five categories (increased from 11.6% in the whole database to 20.0% in the top 50), and water (W) has remained in third place (changed 15.3% in the whole database to 15.0% in the top 50). Landscape research (L) remains in fifth place (decreased from 8.7% in the whole database to just 1.0% in the top 50).

By considering citations per year (CPY) as a measure of impact or importance to the scientific community, the rank order of categories is E > W > P > L > I for the whole database but becomes E > I > P > W > L for the top 50 papers. By then combining the number of papers in each category with the average citations per year (CPY) for the category, this gives the rank order for the whole database as E>W>P>I>L and the ranks for the top 50 papers are the same.

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So, in summary, research concerned with the impacts of climate change on terrestrial ecosystems (E) in polar and mountainous regions dominates, with papers on the impact on water resources (W) being second and a very close third the impact on people’s livelihood (P), with I fourth and L fifth. Landscape (L), in our view, appears to be under researched and is presumably included in the IPCC Terrestrial Ecosystems category. We feel that policy makers should note this under-representation of high impact research into landscape processes (erosion and deposition processes), which needs to be addressed in future. The Interregional Technical Co-operation Project INT/5/153 (2014-18) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions, organized and funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, will address this gap to some extent.

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