

ESEX Commentary

Growing new generations of critical zone scientists

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Earth Surface Processes and Landforms

ABSTRACT: Critical zone (CZ) science is entering its second decade. A new generation of scientists is emerging trained specifically in CZ science and are contributing to advances in environmental science across disciplines. Concurrently, the global scope of CZ science is being elevated as new countries invest in CZ observatories. Global CZ science has great potential to address a diverse array of questions beyond any single discipline. In this commentary we discuss a series of CZ science grand challenges that should be targeted by early-career researchers: understanding water availability in the CZ; expanding CZ science into new environments; communicating the societal relevance of CZ science including *earthcasting* to the public; seamlessly integrating biological sciences within the CZ framework; and scaling CZ processes over large spatial and temporal gradients. Targeting these grand challenges will push CZ science well into the future. We also highlight mechanisms for increased leadership within the CZ community. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS: critical zone science; critical zone observatories; early-career; grand challenges; earth systems research

Introduction

The term *critical zone* (CZ) first appeared in a 2001 publication, Basic Research Opportunities in Earth Science (National Research Council, 2001). The CZ extends from the canopy boundary layer down through the soil and regolith to the bottom of the deepest weathering front. It is this CZ that provides the energy, nutrients, and water needed to sustain terrestrial life, attenuates pollutants, and sequesters carbon. The CZ concept evolved out of discussions on the need for transdisciplinary research to understand the interacting processes that influence and sustain life on Earth. CZ science as a formal discipline is now entering its second decade of US funding and more CZ observatories (CZO) are developing around the world (Guo and Lin, 2016). The CZ spirit of transdisciplinary research seems to be well under way.

Transdisciplinary science requires pushing past traditional disciplinary boundaries, integrating data across spatial and

temporal scales and working towards inclusiveness. To continue making this global idea work, new generations of CZ scientists need to join with early-CZ pioneers to push this science forward. During this past decade, an increasing number of graduate students and post-doctoral researchers received training in CZ science (Figure 1). Much of this training was the direct result of specifically funded research programs including the US NSF funded CZO network and the European SoilTrEC (Soil Transformations in European Catchments) initiative through the European Commission. These CZ scientists are now developing their own careers, and are poised to advance Earth and environmental science, given the depth and breadth of their backgrounds. In this commentary, we outline a series of scientific grand challenges for early-career CZ researchers including: (1) understanding water availability in the CZ; (2) expanding CZ science into new environments; (3) communicating the societal relevance of CZ science including 'earthcasting' to the public; (4) seamlessly integrating biological

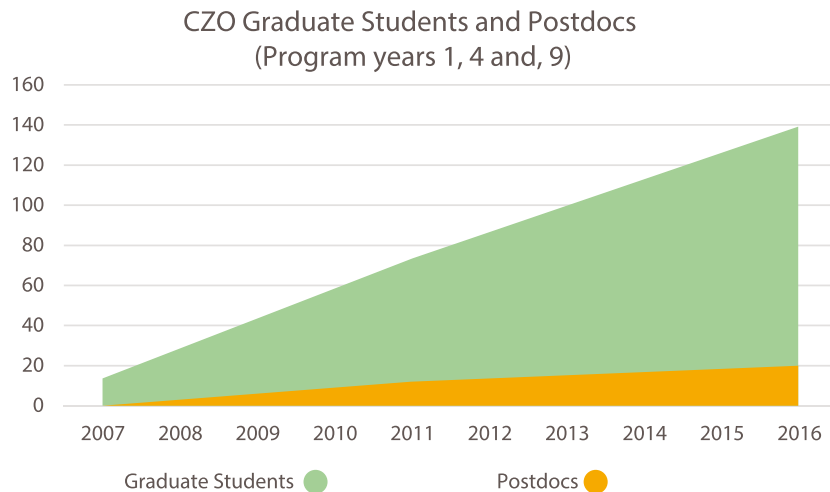


Figure 1. Cumulative growth of graduate students and post-doctoral researchers receiving training in critical zone science. Data were collected from the US Critical Zone National Office and reflect reporting from across the US Critical Zone Observatories. Figure does not represent a complete data set. Actual growth across the entire international CZO program is likely to be much greater than expressed in this figure. [Colour figure can be viewed at wileyonlinelibrary.com]

sciences within the CZ framework; and (5) scaling CZ processes over large spatial and temporal gradients. These objectives reflect feedback received, and observations made, by the early-career cohort. While not the sole domain of early-career researchers, these challenges provide a framework to galvanize future generations of CZ scientists with targeted objectives regarding some of the most urgent questions in environmental science.

Early-Career CZ Grand Challenges

Understanding water availability in the CZ

Water is the primary media by which energy, sediment and solutes move throughout the CZ. Understanding the controls of water, sediment and solutes fluxes remains a fundamental challenge. In addition to human perturbation of the water cycle, ecohydrological models indicate that the residence time and partitioning of water throughout the CZ is highly variable over both space and time (Brooks *et al.*, 2015; Evaristo and McDonnell, 2017). Understanding this variability requires a CZ perspective as the availability of water is driven by hydrological, geological, climatic, pedological, and ecological factors.

One organizing framework helpful in understanding the partitioning of water is that of blue vs green water (Falkenmark and Rockström, 2004), which considers different reservoirs and pathways of water within (and out of) the CZ. Green water represents water moving through evapotranspirative pathways, while blue water is the sum of ground and surface water. Green and blue water both support CZ services (*sensu lato* Field *et al.*, 2015) and both are required for the survival of all organisms. Understanding how water moves between these reservoirs (Bart *et al.*, 2016), should be a central goal as we manage water resources under increasing demand.

Expanding CZ science into new environments

While CZ research occurs across diverse biomes (Figure 2), many environments still remain underrepresented. Three such environments include urban, polar and karst landscapes. Globally, more people live in urban areas than in rural areas.

It is estimated that by 2050, 2.5 billion people will be added to urban centers around the world (World Urbanization Prospects, 2014).

Urbanization increases the rate in which productive agricultural land is lost, increases energy demand, changes regional climates, alters biogeochemical cycles, and reduces biodiversity (Seto *et al.*, 2011). Urban centers also display altered hydrology (Fletcher *et al.*, 2013) and accelerated weathering (Kaushal *et al.*, 2014). It is important for early-career researchers to realize that transferring CZ science into urban landscapes does not require a reconceptualization of the science. CZ science has a rich history of working across environmental gradients, thus working across urban gradients can be pursued in a similar vein.

The Arctic represents another environment relatively unexplored by CZ science. Changes in the Arctic due to global climate change are likely to have disproportionate effects on the biosphere. The Arctic contains 50% of global soil carbon with the majority preserved in permafrost (Schuur *et al.*, 2008). Accelerated rates of warming in the Arctic, have decreased permafrost extent, increased active layer depth, and increased thermokarst processes (Frey and McClelland, 2009) – all of which can release stored carbon. Carbon loss via permafrost thaw and microbial decomposition overwhelms increased rates of plant uptake via warming to such an extent that the Arctic will become a net carbon source to the atmosphere (Schuur *et al.*, 2008). The Arctic is not a homogenous environment; thus, we cannot create a one-size-fits-all model. The extent of discontinuous versus continuous permafrost is highly variable and vegetation is diverse with both tundra and taiga communities. Transdisciplinary CZ science is ideal for this environment as we expect the structure of the Arctic CZ to actively change with profound implications for how the Arctic CZ functions.

Carbonate terrain occupies ~20% of the ice-free terrestrial land (Hartmann and Moosdorf, 2012), supplying potable water to 20–25% of the world's population (Ford and Williams, 2007). On time periods relevant to humans, weathering of these carbonate systems plays a meaningful role ($\sim 1.5 \times$ silicate weathering CO_2 consumption year^{-1} ; Gaillardet *et al.*, 1999) in controlling atmospheric and subsurface CO_2 concentrations (Liu *et al.*, 2011). Given the high energetics of carbonate systems, and their response to changes in climate, sea level and land cover, we can leverage carbonate CZs to directly observe the physical, chemical, and biological consequences of natural



Figure 2. Critical zone science occurs across diverse landscapes. Top Row (L-R): Dr Adrian Harpold (University of Nevada, Reno [UNR]) and Marianne Okal (UNAVCO) discuss the application of terrestrial laser scanning equipment in the Jemez River Basin CZO after the 2013 Thompson Ridge Fire; Dr Daniella Rempe (sitting left; University of Texas, Austin) and Dr Jill Marshall (standing right; University of California, Berkeley) are joined by other Eel River CZO researchers to install sensors and samplers for monitoring the moisture dynamics and chemical evolution of fluids in the critical zone along a steep slope in an old-growth forest in northern California; Patrick Longely (left; UNR graduate student) and Kasey Hewson (right, UNR undergraduate student) collect snowmelt samples to understand the sources and fate of water in the Sagehen Experimental Watershed, near Truckee, California; Bottom Row (L-R): University of Texas, El Paso students Luca Alvarez (right; PhD graduate student) and Victor Garcia (left; undergraduate student), collect irrigation water to study sources of salinity in the Rio Grande, a critical water resource for regional agriculture; Dr Adam Wymore (University of New Hampshire) performing nutrient addition experiments in streams at the Luquillo CZO, Puerto Rico to study carbon and nitrogen biogeochemistry in a tropical landscape; Dr Julia Perdrial (University of Vermont) digging a soil pit for sub-surface instrumentation in a severely burned catchment at Jemez River Basin CZO. [Colour figure can be viewed at wileyonlinelibrary.com]

and anthropogenic forcings on CZ functions. Direct measurements enhance our power in predicting future trajectory of the CZ given modified salinity regimes, water volumes, flow paths, $p\text{CO}_2$, temperature and residence time, all of which govern how CO_2 is absorbed or released from terrestrial landscapes.

Communicating the societal relevance of CZ science including earthcasting to the public

Earthcasting – the projection of Earth’s near surface fluxes of water, solutes and sediments (Goddéris and Brantley, 2013) – is an integrative approach that tackles societally relevant problems including predicting landslide vulnerability, sensitivity of soil development to climate variability and uncertainty surrounding access to potable water. Early-career CZ scientists are key to the construction and use of *earthcasting* models and transmitting this knowledge to the public. One challenge early-career CZ scientists face is communicating that CZ processes occur across multiple temporal and spatial scales, including relatively slow geochemical (10^0 – 10^3 yr) and fast biological (10^{-3} – 10^{-1} yr) processes (Sullivan *et al.*, 2016), and that these timescales need to be considered when developing management plans. Understanding the factors that control erosion, nutrient retention, and carbon sequestration in soils for example, is critical as the global community approaches 9 billion people while dealing with the uncertainty of climate change. Earthcasting via a CZ perspective is ideal to study soils and food production as balancing crop productivity while minimizing soil and water quality degradation is a core challenge facing future CZ researchers.

Seamlessly integrating biological sciences within the CZ framework

By definition, the CZ incorporates all terrestrial life. Biological systems are not just response variables relating to the structure and function of the CZ. Organisms, as well as ecological processes, serve as drivers of CZ processes by altering its inherent structure. While considerable CZ research has examined the effect of microorganisms and trees, the influence of organisms extends beyond these two groups. Prairie dog colonies in semi-arid grasslands promote groundwater recharge, increase soil carbon storage, and provide aeration of soils, promoting plant growth and slowing desertification (Martínez-Estévez *et al.*, 2013). The presence of wolves affects rates of riverbank erosion and soil moisture via predation upon elk and deer (Beschta and Ripple, 2006, 2008). And earthworms serve as a major geologic force moving billions of tons of earth each year, improving infiltration rates and providing channels for root growth. Yet prairie dogs, wolves, and earthworms are subject to ecological processes including predation, competition and disease (Eads and Biggins, 2015). The next-generation of CZ researchers should work to unify the biological sciences with the geological and hydrological sciences moving CZ science into new dimensions.

Scaling CZ processes across large temporal and spatial scales

A hallmark of CZ research is its multiple spatial and temporal scales (Brantley *et al.*, 2007). For example, bedrock weathering can control multiple watershed properties (Rempe and Dietrich,

2014), and frost-driven sediment-production and erosion processes during the last glacial maximum, influence modern soil properties (Marshall *et al.*, 2015). To continue pushing CZ science forward, early-career scientists must continue to consider interactions across large spatial and temporal scales and develop models that cross these boundaries (Figure 3; Duffy *et al.*, 2014; Pelletier *et al.*, 2015; Li *et al.*, 2017).

Cross-CZO collaborations are one way in which spatial and temporal scales can be linked. Many of the CZ pioneers are constrained by the commitments of maintaining their current observatories. Early-career researchers are less encumbered in this respect and are trained to work across environmental gradients where watershed state factors vary. Early-career researchers can also integrate datasets from CZOs with long-term monitoring programs (International Long Term Ecological Research) and spatial products derived from NASA missions.

Accepting Leadership Roles

1. Developing the next generation of CZ scientists

To sustain CZ science into the future, early-career researchers must promote a multigenerational legacy by training future CZ scientists (Figure 2). Training these future practitioners requires developing curricula that integrates geologic, hydrologic, soil, biologic, ecosystem, and atmospheric science with the human and applied aspects of CZ science. Successful examples include an introductory CZ science course (White *et al.*, 2017) offered through the Science Education and Resource Center at Carleton College, and the Environmental Studies major at Roanoke College where CZ science is a core theme. Integrating CZ concepts into current courses is also an effective mechanism. CZ science has been spreading over the last decade as alumni of the CZO program now teach across universities. These individuals incorporate CZ concepts into multiple courses, and as a result, CZ science reaches thousands of students each year. Examples include a Watershed Hydrology course at the University of Minnesota and a Geochemistry of Natural Waters course at the University of Vermont.

Early-career researchers should continue to collaborate with secondary-level educators and develop engaging ways to bring their expertise to these students and educators. Many science courses at the secondary-level would benefit from CZ concepts, exposing younger students to a 'systems' way of thinking. Working with secondary-level students will promote the public awareness of CZ science integrating CZ concepts into the

general public's lexicon. Such outreach efforts can easily be built into the broader impacts section of proposals.

2. Funding opportunities: many exist

To drive CZ science forward, early-career CZ researchers should look toward funding sources that support large collaborative research. Examples include Research Coordination Networks (RCN), Science Across Virtual Institutes (SAVI), and Partnership for International Research and Education (PIRE) through the US NSF. Funding focused on data-syntheses include the Powell Center Grant (United States Geological Survey), the National Center for Ecological Analysis and Synthesis (NCEAS; University of California Santa Barbara), and the Socio-Environmental Synthesis Center (SESYNC; University of Maryland). International funding sources include, the Marie-Sklodowska-Curie Actions through the European Commission and the Chinese Academy of Science and Chinese Scholarship Council which support visiting scholars. These funding sources can be used to bring together researchers where ideas can be fully developed and global-scale hypotheses tested.

3. Outreach: it does not take much to get involved

Early-career researchers can, and should, reach outside the CZ community to increase awareness of the discipline. Such efforts will create a dynamic cross-section of earth and environmental scientists representing multiple world-views (Larsen *et al.*, 2015) while promoting a spirit of inclusiveness. A recent example occurred at the 2015 Ecological Society of America meeting, where a session was hosted encouraging CZ science within the ecological community, 'Ecology from treetop to bedrock: human influence in Earth's critical zone.' Early-career researchers should build the capacity of a global forum that facilitates collaboration and community building. One excellent example is the international web-based community of the Association of Polar Early-Career Scientists (www.apecs.is). Efforts to involve other communities is essential for the future of CZ science and its integration with other networks.

The role of early-career researchers in pushing CZ research forward is pivotal. Cross-CZ science offers an unprecedented opportunity for early-career researchers to jump headfirst into the challenge of transdisciplinary global scale science. CZ science has not yet reached its full potential, but its continued development is a key step in our collective understanding of the interacting factors driving CZ evolution and life sustaining processes.

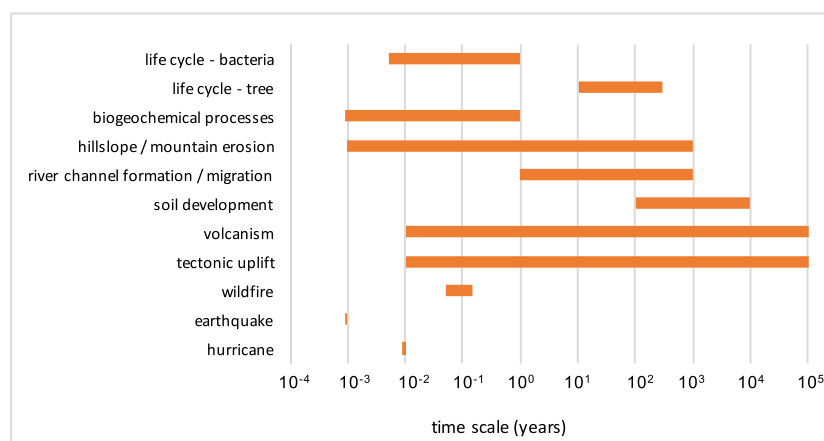


Figure 3. Critical zone scientist work across multiple time scales ranging from seconds to millions of years. Working across multiple time scales is an inherent challenge to CZ science but necessary to understand interacting processes and scale measurements for accurate earthcasting. [Colour figure can be viewed at wileyonlinelibrary.com]

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References

- Bart RR, Tague CL, Moritz MA. 2016. Effect of tree-to-shrub conversion in lower montane forests of the Sierra Nevada (USA) on streamflow. *PLoS One* **11**: e0161805. <https://doi.org/10.1371/journal.pone.0161805>.
- Beschta RL, Ripple WJ. 2006. River channel dynamics following extirpation of wolves in northwestern Yellowstone National Park, USA. *Earth Surface Processes and Landforms* **31**: 1525–1539.
- Beschta RL, Ripple WJ. 2008. Wolves, trophic cascades, and rivers in the Olympic National Park, USA. *Ecohydrology* **1**: 118–130.
- Brantley SL, Goldhaber MB, Vala RK. 2007. Crossing disciplines and scales to understand the critical zone. *Elements* **3**: 307–314.
- Brooks PD, Chorover J, Fan Y, Godsey SE, Maxwell RM, McNamara JP, Tague C. 2015. Hydrological partitioning in the critical zone: Recent advances and opportunities for developing transferable understanding of water cycle dynamics. *Water Resources Research* **51**: 6973–6987.
- Duffy C, Shi Y, Davis K, Slingerland R, Li L, Sullivan PL, Godd  ris Y, Brantley SL. 2014. Designing a suite of models to explore critical zone function. *Procedia Earth and Planetary Sciences*. <https://doi.org/10.1016/j.proeps.2014.08.003>.
- Eads DA, Biggins DE. 2015. Plague bacterium as a transformer species in prairie dogs and the grasslands of western North America. *Conservation Biology* **29**. <https://doi.org/10.1111/cobi.12498>.
- Evaristo J, McDonnell JJ. 2017. Prevalence and magnitude of groundwater use by vegetation: a global stable isotope meta-analysis. *Scientific Reports* **7**. <https://doi.org/10.1038/srep44110>.
- Falkenmark M, Rockstr  m J. 2004. *Balancing water for man and nature: the new approach to ecohydrology*. EarthScan: UK.
- Field JP, Breshears DD, Law DJ, Villegas CJ, L  pez-Hoffman L, Brooks PD, Chorover J, Barron-Gafford GA, Gallery RE, Litvak ME, Lybrand RA, McIntosh JC, Meixner T, Niu GY, Papuga SA, Pelletier JD, Rasmussen CR, Troch PA. 2015. Critical zone services: expanding context, constraints, and currency beyond ecosystem services. *Vadose Zone Journal* **14**(1): <https://doi.org/10.2136/vz2014.10.0142>.
- Fletcher TD, Andrieu H, Hamel P. 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Advances in Water Resources* **51**: 261–279.
- Ford DC, Williams P. 2007. *Karst Hydrogeology and Geomorphology*. John Wiley and Sons: Chichester, UK.
- Frey KE, McClelland JW. 2009. Impacts of permafrost degradation on arctic river biogeochemistry. *Hydrological Processes* **23**: 169–182.
- Gaillardet J, Dupr   B, Louvat P, Allegre CJ. 1999. Global silicate weathering and CO₂ consumption rates deduced from the chemistry of large rivers. *Chemical Geology* **159**: 3–30.
- Godd  ris Y, Brantley SL. 2013. Earthcasting the future Critical Zone. *Elementa: Science of the Anthropocene* **1**. <https://doi.org/10.12952/journal.elementa.000019>.
- Guo L, Lin H. 2016. Critical zone research and observatories: current status and future- perspectives. *Vadose Zone Journal* **15**. <https://doi.org/10.2136/vzj2016.06.0050>.
- Hartmann J, Moosdorf N. 2012. The new global lithological map database GLIM: a representation of rock properties at the Earth surface. *Geochemistry, Geophysics, Geosystems* **13**: Q12004.
- Kaushal SS, McDowell WH, Wollheim WM. 2014. Tracking evolution of urban biogeochemical cycles: past, present, and future. *Biogeochemistry* **121**: 1–21.
- Larsen L, Hajek E, Maher K, Paola C, Merritts D, Bralower T, Mont   ez I, Wing S, Snyder N, Hochella M, Jr, Kump L, Person M. 2015. Taking the pulse of the Earth's surface systems. *Eos* **96**. <https://doi.org/10.1029/2015EO040525>.
- Li L, Maher K, Navarre-Sitchler A, Druhan J, Lawrence C, Meile C, Moore J, Perdial J, Sullivan PL, Thompson A, Jin L, Bolton E, Brantley S, Dietrich W, Mayer U, Steefel CI, Valocchi A, Zachara J, Kocar B, McIntosh J, Tutolo BM, Beisman J, Kumar M, Sonnetal E. 2017. Expanding the Role of Reactive Transport Models in Critical Zone Processes. *Earth-Science Reviews* **165**: 280–301.
- Liu Z, Dreybrodt W, Liu H. 2011. Atmospheric CO₂ sink: silicate weathering or carbonate weathering? *Applied Geochemistry* **26s**: 292–294.
- Marshall JA, Roering JJ, Bartlein PJ, Gavin DG, Granger DE, Rempel AW, Praskievicz SJ, Hales TC. 2015. Frost for the trees: did climate increase erosion in unglaciated landscapes during the late Pleistocene? *Scientific Advances* **1**. <https://doi.org/10.1126/sciadv.1500715>.
- Mart  nez-Est  vez L, Balvanera P, Pacheco J, Ceballos G. 2013. Prairie dog decline reduces the supply of ecosystem services and leads to desertification of semiarid grasslands. *PLoS One* **8**. <https://doi.org/10.1371/journal.pone.0075229>.
- National Research Council. 2001. *Basic research opportunities in Earth Science*. National Academies Press.
- Pelletier JD, Brad Murray A, Pierce JL, Bierman PR, Breshears DD, Crosby BT, Ellis M, Foufoula-Georgiou E, Heimsath AM, Houser C, Lancaster N. 2015. Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future* **3**: 220–251.
- Rempe DM, Dietrich WE. 2014. A bottom-up control on fresh-bedrock topography under landscapes. *Proceeding of the National Academy of Sciences* **111**: 6576–6581.
- Schuur EAG, Bockheim J, Canadell JG, Euskirchen E, Field CB, Goryachkin SV, Hagemann S, Kuhry P, Lafleur PM, Lee H, Mazhitova G, Nelson FE, Rinke A, Romanovsky VE, Shiklomanov N, Tarnocai C, Venevsky S, Vogel JG, Zimov SA. 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *Bioscience* **58**: 701–714.
- Seto KC, Fragkias M, Guneralp B, Reilly MK. 2011. A meta-analysis of global urban land expansion. *PLoS One* **6**: e23777. <https://doi.org/10.1371/journal.pone.0023777>.
- Sullivan PL, Ma L, West N, Jin L, Karwan DL, Noireaux J, Steinhofel G, Gaines KP, Eissenstat DM, Gaillardet J, Derry LA, Meek K, Hynek S, Brantley SL. 2016. CZ-tope at Susquehanna Shale Hills CZO: synthesizing multiple isotope proxies to elucidate Critical Zone processes across timescales in a temperate forested landscape. *Chemical Geology* **445**: 103–119.
- White TS, Wymore AS, Dere A, Hoffman A, Washburne J, Conklin M. 2017. Integrated interdisciplinary science of the Critical Zone as a foundational curriculum for addressing issues of sustainability. *Journal of Geoscience Education* **65**: 136–145.
- World Urbanization Prospects. 2014. The 2014 Revision, Highlights. Department of Economic and Social Affairs. Population Division. United Nations. New York.