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Pedagogy for the pedosphere

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already under severe pressure from overfishing (Tweddle *et al.* 2015).

Although the consequences of this invasion are difficult to predict, there is already evidence of its disruptive effects. On the Kafue Flats, artisanal fishermen have reported substantial damage to fish caught in gill nets, as well as to the nets themselves, by scavenging crayfish (Phiri 2009; Tyser 2010). Crayfish caught in nets are generally discarded, as local superstitions seem to inhibit the eating of crayfish/shellfish and there is no local market for them. In both Zambia and South Africa, populations of C *quadricarinatus* have been responsible for the introduction of an undesirable non-native temnocephalan ectoparasite that might be harmful to native decapods (du Preez and Smit 2013; RJD personal obs). Furthermore, although some predatory fish species in the Kafue region have incorporated crayfish into their diets, positive impacts linked to the availability of a new prey species are likely to be limited, as crayfish have relatively low energy content in comparison to fish prey (Elvira *et al.* 1996). It is also doubtful that fish predation will deplete crayfish populations, because only small-sized crayfish seem to be vulnerable to this (Tyser and Douthwaite 2014). As such, research to identify the extent of this invasion – as well as the impacts on native biota linked to the role of C *quadricarinatus* as a predator, competitor, habitat disruptor, and parasite carrier – is urgently required.

Given the rapid spread of this species, it is important to develop proactive management and control/eradication measures to prevent further spread and mitigate invasion-related impacts. Crayfish control can be attempted through mechanical (trapping and electrofishing), physical (draining water bodies or creating barriers), chemical (use of biocides), or biological (microbial insecticides and introduction of fish predators) techniques (Freeman *et al.* 2010). However, since complete eradication is not realistic for established and abundant crayfish populations (Gherardi 2007), in order to stop or hinder crayfish invading the Okavango Delta, immediate action is needed to determine whether eradication at Mongu is still feasible, or if measures to reduce crayfish abundance through a combination of intensive trapping and chemical control between two physical barriers on the Selinda Spillway should be implemented. In addition, legislation restricting the movement of the species and education of local people on the dangers of promoting the spread of this alien invader are necessary. While these are not definitive solutions, and will be difficult and costly to implement, failure to control the spread of this crayfish will most likely have enormous adverse consequences for the ecological structure and functioning of the Okavango Delta ecosystem.

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Pedagogy for the pedosphere

The United Nations designated 2015 as the International Year of Soils (IYOS), which reminded us of the irreplaceable value of the pedosphere – the Earth's complex, dynamic layer of soil – for supporting human well-being. During the year, a series of high-profile articles emphasized the research, policy, and governance dimensions of soils (Amundson *et al.* 2015; Nielsen *et al.* 2015; Oldfield *et al.* 2015; Wall and Six 2015; others listed at www.nature.com/soils). Although essential, advancing these aspects alone will be insuffi-

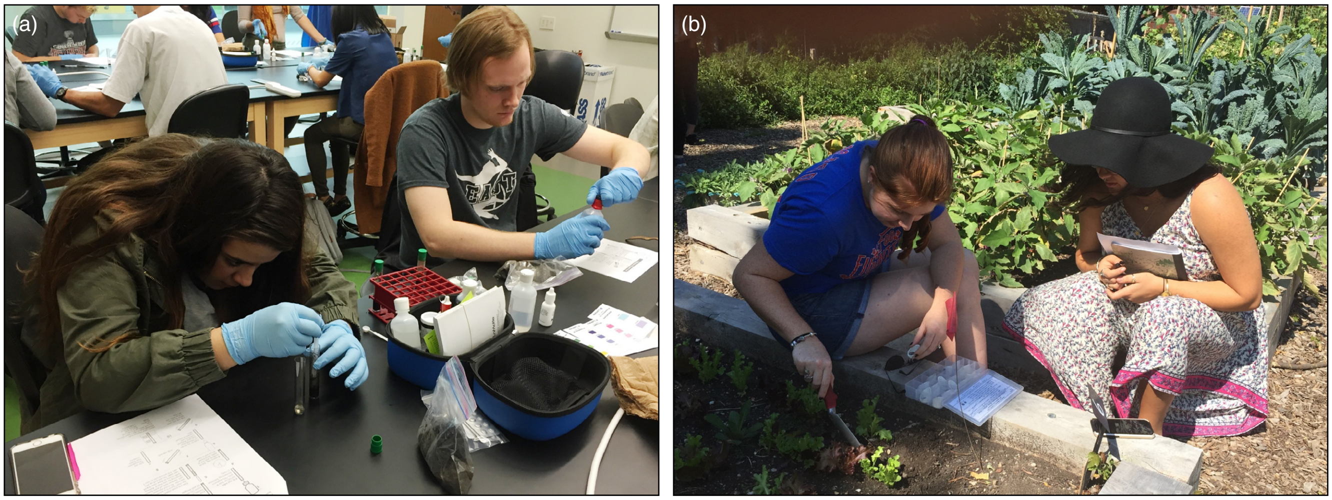

Figure 1. *"Pedagogy for the pedosphere" promotes hands-on and inquiry-based learning activities to enhance students' soil literacy, including (a) laboratory analyses that also help students develop basic skills and (b) field work that provides opportunities to apply soil-systems concepts to issues such as sustainable agriculture.*

cient to make progress in "saving our soils". Here, we highlight an equally important issue that has been given less attention: the necessity of strengthening and expanding environmental soil-systems education at the K–12, undergraduate, and graduate levels (FAO and ITPS 2015). We suggest that scientists and educators of all types should devote more attention to developing and implementing "pedagogy for the pedosphere" – innovative, interdisciplinary, systems-based education grounded in the study and appreciation of soils, their ecology, and their vital human relationships. Because of their numerous unique qualities, soils can advance many science, technology, engineering, and mathematics (STEM) – and non-STEM – educational goals across student levels and interests, and can be integrated into diverse educational experiences in many ways.

The benefits of soils as focal points for STEM education are multifaceted. The pedosphere – formed at the intersection of the atmosphere, lithosphere, hydrosphere, and biosphere – is exceptionally conducive to integrating physics, chemistry, geology, biology, and mathematics to help students develop holistic, interdisciplinary views of science and the environment (Field *et al.* 2011). As such, the study of soil systems can easily support many crosscutting and core concepts that have been proposed as foci for science education reforms at K–12 and undergraduate levels (eg energy/matter fluxes, systems thinking, and others identified in Brewer and Smith [2011] and NRC [2012]). Pedagogically, soils can be used in learner-centered, inquiry-focused, and project-based lessons that help students develop key scientific practices including quantitative analysis, problem solving, synthesis, and evidence-based reasoning (eg Johnson *et al.* 2009; Moebius-Clune *et al.* 2011; Magee and Wingate 2014; Thiet 2014; Krzic *et al.* 2015; Baum and Thiet 2016). Furthermore, soil organisms can provide the seldom-considered ecosystem service of inspiring wonder and curiosity in students who often do not know about the astonishing diversity and ecology of belowground life.

Soils and their organisms are, literally, everywhere and are easy to observe and collect in the field – even in urban environments, where teachers may be challenged to develop environmental lessons (Johnson and Catley 2009). Thus, nearly all educators can access soils to develop site-specific curricula, hands-on demonstrations, and research projects tailored to their student populations (Figure 1). For example, students can investigate the soils of their school's campus grounds by comparing how they differ among lawns, gardens, and other local habitats (eg Byrne *et al.* 2008). In our experience, even simple, short-term lessons and field trips that have students (of any level, from elementary to graduate) observe and dig into soils with their "naked eyes and hands" and search for soil "critters" (as in a competitive scavenger hunt) enhance their soil-oriented awareness and create meaningful, teachable moments. Such place-based lessons help catalyze discussions about the personal relevance and local-scale sustainable management of soils while connecting science to students' everyday lives (eg the ecology of their neighborhoods).

Soils should also become a more central focus for STEM education because soil literacy is required for informed environmental citizenship, particularly in the context of food production and security, climate regulation, water purification, and other critical services (Amundson *et al.* 2015). Without soil education, future scientists, educators, policy makers, and land managers, among many others, are less likely to consider soils in their decisions, which will undermine policy making and scientific efforts to increase the sustainability of soil systems. Fortunately, the diversity of human–soil relationships facilitates the teaching of science–society connections and reinforces the value of using scientific evidence in problem solving (Krzic *et al.* 2015). Thus, in both STEM and general education courses across student levels, a more concentrated focus on soil education is needed to ensure that all students – regardless of their interests, majors, and future careers – learn that soils are complex, yet fragile systems that affect their daily lives. Citizens that have such soil literacy can engage in decision making that promotes soil sustainability at backyard, watershed, and global scales (Field *et al.* 2011).

To these ends, more focused, sustained, and widespread efforts are needed to develop and implement – in our labs, classrooms, and communities – innovative, scalable, and easily accessible soil-systems education resources (eg see the teaching-activity articles cited above). In addition, soil-focused professional development opportunities for educators should be offered widely to enhance their capacities for teaching about, and with, soil systems, using high-impact practices (FAO and ITPS 2015). Such investments are crucial for fostering a more soil-literate – and science-literate – populace, which in turn is needed to support further progress in addressing society's many soil-related security and sustainability challenges (Amundson *et al.* 2015). Although the IYOS has now passed, soil-systems education remains an essential foundation for ensuring humanity's long-term well-being. We therefore encourage all scientists and educators to collaborate and increase their engagement in the critical work of advancing "pedagogy for the pedosphere".

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