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Nov. 29, 2009

Dr. Hans-Jörg Vogel
Guest editor of HESS

Dear Hans-Jörg,

First of all, thanks for your patience in receiving my delayed revision of the manuscript submitted to the special issue of HESS, entitled "***Earth's Critical Zone and Hydropedology: Concepts, Characteristics, and Advances***" (***hess-2009-95***). I have now finally completed a thorough revision according to all the review comments received. I do appreciate the time the reviewers and you put in reading the manuscript, and the comments were valuable, refreshing, and constructive. I have carefully considered and incorporated, where appropriate, all the review comments in the revision. While the 2nd reviewer suggested a focus on the Critical Zone part, you suggested a focus on the hydropedology part. Hm … In the end, I managed to maintain a balance between the two parts while still shortened the manuscript considerably (the text has been cut to 28 pages from the original 38 pages, with the figures reduced to 9, and the manuscript reduced to 49 total pages instead of original 63). The reason that I decided to keep both the Critical Zone part and hydropedology part was the merit of linking the two topics and my intent to use hydropedology to illustrate the opportunity associated with the CZ study — this also matches the theme of the special issue. I hope you like the more tightly-coupled and considerably-shortened manuscript. A list of itemized responses to all review comments is attached at the end of this letter, along with a change-tracked copy of the revised manuscript. Hopefully, I have adequately addressed all the review comments to your satisfaction. Should you have any further comment or need more information or action from me, please let me know.

Thanks for your further consideration of this manuscript.

Sincerely Yours,

Henry Lin
Associate Professor of Hydropedology/Soil Hydrology

Encl.: 1) Revised manuscript (clean copy)
2) Item-by-item responses to all the review comments, plus an annotated version of the revised manuscript (changes marked using Word "Track change" function)

Item-by-item responses to all review comments

NOTE: To facilitate the evaluation of my responses, original review comments are listed first in their originals (in black), followed by my itemized responses ***(in red, italic and bold)***. See the attached annotated version of the revised manuscript for specific verification.

Comments from the editor

I concur with Reviewer #2 that the paper is quite long and that it could be shortened to some extend without loosing essential messages. Thereby I would prefer the second option mentioned by the reviewer: to shorten the first part on the definition of the CZ. I think the readers of HESS are well aware that the zone between the lower atmosphere including vegetation and the the lower boundary of the aquifer is a inherently complex systems demanding for an interdisciplinary scientific approach. So that all these different definitions are not really required but of course (as also stated by the reviewer) there should be a clear definition what you refer to as the 'Critical Zone'. This is required for the further discussion of how hydropedology fits into this concept. I really liked the way how hydropedology is introduced! In my perception there are some new inspiring aspects. On the other hand, there is no general agreement within the soil science community about the general aims and scopes of hydropepdology. Hence, this part of the manuscript is especially valuable. It could be argued that there have been other papers on hydropedology already, however I recognize that with the present manuscript the notion of hydropedology is becoming more clear, more focused, and better justified.

Thanks for your thorough comment. As indicated in my cover letter above, I have shortened the whole manuscript considerably (the text has cut to 28 pages from the original 38 pages). I have, however, decided to maintain a balance between the two interrelated topics (the CZ and hydropedology) because of the merit of linking the two and my desire to use hydropedology as an illustrative example of the CZ study. I have clarified the definition of the CZ, and stated its definition from NRC (2001) upfront in the 2nd sentence in the Introduction part. I have maintained the part that you like, but rearranged the sequence based on the 2nd reviewer's suggestion. In discussing the fundamental issues of hydropedology, I have condensed considerably by providing only updates, and referred the readers to a more comprehensive review that I published in 2005.

I have a few additional minor comments:

P2 L1: the increasing characteristic time for response and feed back with depth is motivated by the increasing density of the material (also later in the text). Isn't it more the increasing distance to the location of energy input (the soil surface) and the dampening of the dynamics of state variables with depth?

Good comment! I have incorporated this suggestion into the revision.

Section 2.1: As already mentioned above this could be shortened considerably.

Section 3.2.3: There is some redundancy in this section so that it could also be shortened to some extend.

Done as suggested.

4.1. Mapping: It could be emphasized more explicitly that we can use our knowledge of soil formation and the known interrelation of soils within landscapes to establish a mapping strategy which is supported by a sort of soil-landscape modeling. The latter can be developed from the answers to the two basic questions formulated in section 3.1.

Good suggestion. Revised accordingly.

4.3. Modeling: I agree that network structures are very common in terrestrial systems and that they are very likely to exist also in the subsurface. However I would expect that theses structures are highly variable within the vadose zone and highly dependent on the hydraulic state of the system. Hence, a discrete representation of preferential flow networks within the subsurface can hardly be mapped and is probably not adequate. This phenomena could be reflected e.g. by appropriate travel time distributions in large scale models - but this is a matter of future inspiring discussions between the author an the handling editor...

This is a valid debate. I understand your concern and have indicated this in the revision. Like we discussed in Pittsburg, this is an interesting and inspiring topic to continue to explore from our two different perspectives. Hopefully we would converge somewhere in the middle! I have referred to my JoH manuscript (Lin, 2010a) in the revised manuscript for further related discussion.

Reviewer 1

Comments and edits - Earth's Critical Zone and. Hydropedology
Abstract
P3418
LT4 -Advance
LI4 - Delete'growth'
Ll5 - instead of 'platform', perspective or concept
L26 - instead of 'are linked'. can be addressed
P3419
Ll - remove 'and pedogenesis'
L3 . instead of carriers, vehicles for expression of
P2I - replace 'it is called' with the descriptor
P3420
L23 - change 'coming ...breakthroughs' to 'is becoming united because of the current global concern for the fresh water supply'
And delete "has embraced...relevance" with 'particularly driven by society's need for energy'

P3421
Ll - replace An...fostering' with 'A'
P3424
Llz - replace 'guide......illustration is the' with 'see their knowledge in a wider context e.g knowledge of soil forming processes can provide...
P3427
L22 - replace 'rock' with lithologic.
P3428
Ll6 - remove'maybe called' and'increasingly'
P342g
Ll7 - replace 'as' with because
P3432
L29 - forcings, not forcing.
P3433
Ll - comment only: When undergrads get'wind' of soils with 'hot moments' and 'hot-spots' we'll soon solve our student number crisis.
P3435
L20 - after 'interactions' insert 'of processes.
L25 - replace'while' with whereas
P3436
L4 - aftei.'detaif insert 'than in a previous sfudy' or 'than in previous studies'
L18 - after 'spectroscopic' add 'mathematical and computational'
P3438
Ll6 - replace 'this includes' with'these include'
P3439
3.2 Fundamentals of hydropedology
Revised this whole section to read:
Fundamental scientific issues of hydropedology can be considered under four headings (Fig 6):
1. Soil structure and horizonation. These determine flow and transport characteristics in field soil. Hydropedological studies focus on quantiffing soil architecture and its impact on preferential flow across scales
2. Soil catena and distribution pattem. These properties are the first 'control' of water movement over the landscape. Hydropedological studies embrace quantitative soillandscape relationships and their impact on landscape hydrological processes
3. Soil morphology. Hydrological processes leave signatures in soils. Hydropedology studies focus on quantitative . . . .records.
4. Soil functional classification and mapping. These are'carriers' of hydrological properties. .landscape.
L20 e.21 - delete'one'
L22- delete'further'
P3440
L7,8 - delete 'are of essence to' and replace with is the essential elementt
P344t
LL9- hydrologic

P3449
L7,8 - delete 'on...represent' replace with 'delineations representing spatially'
P3453
Llz- Add 's' after DEM
P3455
L20 to 29 - delete 'soil' after each of the nurnbered points from (1) to(7) and also 'of our soil'
P3459
L23-27 suggest this phrasing neither quickly intermix (cf. atmosphere), nor rapidly move laterully along the landscape (cf. hydrosphere) nor clearly. ....changes (bio sphere), nor escape. . . . .perturb ations (cf lithosphere).
P3460
Ll -'formed-in-situ'
L7&8 - remove 'soil'
Figure I
Delete An...science. Replace with 'A vision for soil science'.

All the above suggested edits have been incorporated where appropriate.

I'm not so comfortable with 'outward growth' and 'inward contraction' preferring descriptors such as "narrow perspective" and 'broad or expansive perspective" Adoption of the broad viedperspective will ensure the growth of soil science and recognition of its relevance in many areas of societal need.

I have adopted the suggested "broad" vs. "narrow" perspectives, but also keep the original labeling to more vividly convey my message. See the revised Fig. 2.

Reviewer 2

The paper of Herny Lin on the "Earth's Critical Zone and hydropedology: concepts, characteristics, and advances" is a timely and important contribution to the science of terrestrial processes and systems as well as to the discussion on the challenges in terrestrial research for the 21th century. It points out the necessity of an integrated approach that needs to be embedded in a holistic perception of the interaction between the different compartments of the Earth's system. Specifically the paper addresses the interaction between the CZ concept and the recently emerged new discipline "hydropedology".

Thanks for this positive feedback.

Although I am convinced that the critical zone is an excellent concept to point out the importance of this thin layer (compared to the Earth's diameter) embracing the Earth, I feel that there is a need for a clear definition of what exactly the Critical Zone is referring to. In the paper there are many tentative descriptions of what a CZ is or is not, but still a clear formulation is missing and in my opinion it is needed in order to provide a consistent discussion throughout the paper. Is the CZ an holistic framework for integrating studies of water, soil, rock, air and biotic resources in terrestrial environments (line 2, page 3418), a platform for synergetic collaboration across disciplines (line 16, page 3418) or is it the heterogeneous near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources (line 5, 3422). In the first definition it is not a natural system whereas in the last one it is. Yet another definition can be found at line 23, page 3430 where the CZ is defined as the zone where all humans live and where population growth, urbanization, and industrialization all have put increasing pressure on the CZ. The author should use a consistent definition of CZ throughout the paper and then derive the research needs and scientific questions. I propose to provide a definition of CZ at the end of section 2.1 and to work with this definition throughout the paper.

Sorry about the confusing CZ definition(s) in the draft manuscript. I have now clarified the definition of the CZ and stated it upfront in the 2nd sentence of the Introduction section in the revision.

The paper is very long and I think it can be shortened without loosing much of its messages. The paper suffers a bit from the fact that it wants to present both the concepts, characteristics and advances for the Critical Zone (and CZ research/science) and hydropedology and at the same time it aims at addressing and discussing the link between both of them. It might be better to focus on either the Critical Zone, the relevant scientific questions, the methods and approaches needed to solve these questions and its links with other disciplines (hydropedology being one of them) or to focus on hydropedology and the role CZ can play in advancing this field of research. Focussing on the Critical Zone has a major advantage as it will allow identifying the contribution needed from all geoscience disciplines rather than from hydropedology alone. In addition, it would be good to point out the new elements added in the discussion and presentation of hydropedology with respect to other publications on this topic.

This is a good thinking and a valuable suggestion. I agree that the draft manuscript was too long. As explained in the cover letter above, I have now shortened the whole manuscript considerably (the text has cut to 28 pages from the original 38 pages). After weighing the two options nicely suggested, I figured that it would still be better (and possible) to maintain a balance between the two interrelated topics (the CZ and hydropedology) because of the merit of linking the two and my intent to use hydropedology to illustrate the opportunities associated with the CZ study. .

In discussing hydropedology, I have condensed considerably by providing only an update on new elements, with respect to other publications on this topic. The readers are referred to a more comprehensive review that I published in 2005 for further details.

Specific comments:

It would be useful to the readers to set CZ in a perspective with respect to ongoing activities of establishing ecological, hydrological and environmental observatories worldwide and to work out the difference and eventual overlaps between the different approaches underlying these observatories. It would also be good to address briefly the actual state of the three Critical Zone Observatories established in the US since 2007. This might be helpful to better understand the underlying approaches and the observation strategies implemented at these sites. What are the lessons learned and what are the future developments in terms of modelling and monitoring?

This is a valuable suggestion and one that is important to pursue. This will be addressed (in a more comprehensive way) in a planned special issue of Vadose Zone Journal focusing on the CZOs (to be published in a year or two). Considering the already long manuscript, I decided not to expand on this important aspect related to ongoing activities of establishing ecological, hydrological and environmental observatories worldwide (there are so much out there – so to do a good job, it would require a thorough study and comparison, which will be difficult to do in a short paragraph). I did, however, provide a brief update on the status of the CZOs in the U.S. and elsewhere. I have also expanded the discussion on key approaches or steps to take for advancing CZ science based on the experience accumulated so far with the CZOs in the U.S. The revised manuscript has strengthened this aspect in Section 4.

The use of the word cycle in section 2.2.1 with respect to geology and biology (geological and biological cycle) seems to me not the right wording with respect to the key processes occurring in the CZ. Basically the Earth system is a system under evolution and this evolution is not necessary happening in a cyclic manner. Many of the important changes have been introduced by extreme events or sudden changes in environmental conditions. Typically a cycle refers more to a specific component that is altered in a cyclic manner such as water in the hydrologic cycle or organic matter in the carbon cycle. Therefore, I suggest the use of geological and biological processes that operate at different spatial and temporal scales rather than focussing on the cyclic nature. The term coupled systems is not really addressed in this section. It would be good to elaborate more on this issue by specifically addressing how the various subsystems of the CZ are coupled and which processes and feedbacks mechanisms are involved. Why is it e.g. important to couple systems and what are the challenges and deficits in our understanding. Interesting issues are e.g the effect of changing groundwater levels on the energy balance at the soil surface and its impact on local meteorology (e.g. Maxwell and Kollet, 2008), the coupling between the subsurface environment and river systems (Sophocleous M, 2002) or the interaction between the atmosphere and terrestrial ecosystems (E.g. Pielke et al., 1998).

This is a very much appreciated reminder that has led to me to add a completely new section in the revision on the evolution aspect of the CZ (Section 2.2.1). I have also beefed up the discussion on coupling aspects and have added all the suggested examples (and more) into the related discussion. I also added a new Fig. 3 to provide more a systems view of the CZ and its general characteristics that include irreversible evolution, coupled cycling, interactive layers, and hierarchical heterogeneity. The use of the word cyclic is kept for geological and biological cycles, but the statements have been improved to avoid possible confusion.

Also in section 2.2.1 the author states that the formation of the CZ is mainly attributed to the impact of geological and biological activity. However, the CZ is also the result of past and present human activity (e.g. land use change from forest to agricultural land) or the presently ongoing climate change in many regions of the world. As the CZ is the skin of the Earth, these activities are more likely to shape the future of this zone rather than the geological processes occurring at larger time and space scales. It should also be made more explicit in how far e.g. tectonic processes (section 2.2) are relevant for processes occurring in the CZ.

I agreed with this comments. I have strengthened the discussion on human impacts in the CZ in several places of the revised manuscript. In the end of the manuscript (last sentence of the summary and conclusion section), I clearly highlighted that human impacts, along with the hydrologic cycle, deserve elevated attentions in the study of the CZ.

In the discussion on heterogeneity and hierarchical patterns it would be useful to start off with presenting the types and scales of heterogeneity encountered in the CZ. These scales may include the local scale, the field/hillslope scale, the catchment and regional scale. At each scale specific heterogeneities are occurring. At the local scale, heterogeneities may e.g. be determined by variability in physical/chemical/biological properties whereas at the catchment scale variability and patterns in soils and vegetation may be more typical. By using these scales one automatically includes a horizontal component in the presentation of the CZ which is important especially when one wants to focus on water as the key driver for many processes in the CZ.

This is a valid point. I have revised the manuscript accordingly. A more focused diagram showing the hierarchy of scales is shown in new Fig. 5, along with added discussion on three types of systems. I also added the discussion on the related controls on patterns in Section 3.1.2.

An important element of the CZ is the presence of interfaces between two or more compartments. The role of these interfaces in understanding the interactions and feedbacks between the different compartments and their regulatory impact on many processes and compartments of the Earth system (e.g. land surface atmosphere interaction; soil-groundwater-river interaction) is essential and should deserve more attention in terms of defining research questions for these interfaces. Perhaps it would be good use the presence of key interfaces in CZ as a part of its definition and uniqueness.

Another very good point. I have stressed more on the interfaces in the revised manuscript. I have also added some discussions through some examples.

I propose to start the section 3 with the fundamentals of hydropedology (now 3.2) and then present the characteristics and its links to CZ science. The paper would benefit from a more explicit definition of Critical Zone science. What is the CZ science and which disciplines does it cover?

Revised accordingly.

Some of the important features of hydropedology (line 16, page 3437) are not really unique to this discipline such as “opening the black box of the soil system by closely examining soil structural heterogeneity and soil distribution pattern in the landscape, rather than treating soil as a simple homogeneous layer” or viewing the soil as a living entity. These assets belong to many soil science disciplines. In the scientific questions, the author refers to landscape water but does not really define what he means by this. Is landscape water the water that does not enter the soil profile and is lost by surface runoff to the river system, or is it the water that is contained in surface water systems? A clarification would be helpful to the reader. As mentioned above, research on the role and importance of interfaces between the hydrosphere (e.g. rivers, groundwater) and the soil appears to me an important asset of hydropedology.

As the handling editor indicated, he liked what was written in introducing hydropedology in the original draft manuscript and the related discussion on its features. So I tried to maintain this part without too much change in the message. However, I did re-word some sentences to avoid such possible arguments. I have clarified what "landscape water" is right after the 2nd question in the beginning section on hydropedology. Interfaces are again better emphasized in the revised manuscript.

The summary and conclusion are very general and would benefit from a more focussed and specific formulation of key steps or actions that need to be taken in order to achieve advancements in our understanding of the functioning of the CZ. The establishment of a global alliance for monitoring-mapping-modeling is one of these steps that need to be taken but most likely not the only one.

Good reminder – I have completely re-written this section to be more focused and specific. Hopefully the new summary and conclusion section reads better.

References:

Maxwell R.M. and S. Kollet, 2008. Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nature Geoscience, 1(10): 665-669.

Pielke R.A., R. Avissar, M. Raupach, A.J. Dolman, X.B. Zeng, and A.S. Denning, 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Global Change Biology, 4(5), 461-475.

Sophocleous M., 2002. Interactions between groundwater and surface water: the state of the science. Hydrogeology journal, 10(1): 52-67.

Good references – I appreciate this effort to list them. All these papers are added to the revision.

Earth's Critical Zone and Hydropedology: Concepts, Characteristics, and Advances

Henry Lin

The Pennsylvania State University, Department of Crop and Soil Sciences, 116 Agricultural Sciences and Industry Building, University Park, PA 16802, USA

Correspondence to: H. S. Lin (henrylin@psu.edu)

Abstract

The Critical Zone (CZ) is a holistic framework for integrated studies of water with soil, rock, air, and biotic resources in the near-surface terrestrial environment. This most heterogeneous and complex region of the Earth ranges from the vegetation top to the aquifer bottom, with a highly variable thickness globally and a yet-to-be clearly defined lower boundary of active water cycle under unsaturated conditions. Interfaces among different compartments are critical to the CZ, which provide fertile ground for interdisciplinary research. The reconciliation of coupled geological and biological cycles (vastly different in space and time scales) is essential to understand the complexity and evolution of the CZ. Irreversible evolution, coupled cycling, interactive layers, and hierarchical heterogeneity are characteristic of the CZ, suggesting that forcing, coupling, interfacing, and scaling are grand challenges for advancing CZ science. Hydropedology—the science of the behaviour and distribution of soil-water interactions in contact with mineral and biological materials in the CZ—is an important contributor to the CZ study. The pedosphere is the foundation of the CZ, which represents a geomembrance across which water and solutes, as well as energy, gases, solids, and organisms are actively exchanged with the atmosphere, biosphere, hydrosphere, and lithosphere, thereby creating a life-sustaining environment. Hydropedology emphasizes *in situ* soils in the landscape, where distinct pedogenic features and soil-landscape relationships are essential to understand interactive pedologic and hydrologic processes. Both CZ science and hydropedology embrace an evolutionary and holistic worldview, and offer stimulating opportunities for advancements through integrated systems

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approach, evolutionary mapping-monitoring-modeling framework, and fostering a global alliance. Our capability to predict the behaviour and evolution of the CZ in response to changing environment can be significantly improved if networked cross-site scientific comparisons, evolutionary treatment of organized complex systems, and deeper insights into the CZ can be implemented.

1 Introduction

"*Our own civilization is now being tested in regard to its management of water as well as soil.*"

— Daniel Hillel (1991)

The U.S. National Research Council (NRC) recommended the integrated study of the "Critical Zone" (CZ) as one of the most compelling research areas in Earth sciences in the 21st century. This CZ is defined by the NRC (2001) as "*a heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources.*" This zone ranges from the top of the vegetation down to the bottom of the aquifer (Fig. 1), and encompasses the near-surface biosphere and atmosphere, the entire pedosphere, and the surface and near-surface portion of the hydrosphere and lithosphere (Fig. 2). The U.S. National Science Foundation (NSF AC-ERE, 2005) also recommended a focus on water as a unifying theme for understanding complex environmental systems. Water-related research requires enhanced understanding of processes at environmental interfaces, approaches for integrating across scales, and improved coupling of biological and physical processes. Collectively, such an integrated, interdisciplinary, and multiscale effort will advance our ability to forecast and plan for changes and to address critical societal issues such as human safety, human health, economic prosperity, environmental quality, and sustainable development.

Soil is at the central junction of the CZ, representing a geomembrane across which water and solutes, as well as energy, gases, solids, and organisms are actively exchanged with the atmosphere, biosphere, hydrosphere, and lithosphere, thereby creating a life-sustaining environment (Fig. 2). Water is the circulating force that drives many of these exchanges and is the major transport agent in the cycling of mass and energy in the CZ. Water flux into and through the soil and over the landscape is the essence of life, which resembles the way that blood

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circulates in a human body (Bouma, 2006). The interactions of soil and water are so intimate and complex that they cannot be effectively studied in a piecemeal manner; rather, they require a systems and multiscale approach. In this spirit, hydropedology has emerged in recent years as an intertwined branch of soil science and hydrology that addresses the interface between the pedosphere and the hydrosphere, with an emphasis on *in situ* soils in the landscape (Lin, 2003; Lin et al., 2006a).

The pedosphere is a unique, relatively immobile sphere that is easily impacted by human activities. In contrast to the other spheres of the Earth system, the pedosphere can neither quickly intermix (as the atmosphere does), nor rapidly move laterally along the landscape (as water does), nor clearly be separated into individual units and avoid undesirable environmental changes (as the biota can be and does), nor escape rapid human and biological perturbations (as is characteristic of the lithosphere). Therefore, each soil, as a relatively immovable and formed *in-situ* natural body, is fated to react, endure, and record environmental changes by being transformed according to the interactions of climatic, biotic, and anthropogenic forcing, as conditioned by geologic and topographic setting, over geological and biological time scales. This makes the monitoring of soil change an excellent (albeit complex) environmental assessment, because every block of soil is a timed "memory" of the past and present biosphere-geosphere dynamics (Arnold et al., 1990). This memory takes multiple forms, such as micromorphology, profile features, and various soil physical, chemical, and biological properties. Learning to "decode" soil features and their changes into environmental information is as valuable as reading the records of ice cores for atmospheric conditions and interpreting tree rings for eco-climatic dynamics.

Given the emerging interests in the CZ, hydropedology, and associated efforts in establishing environmental observatory networks around the world, this article reviews and discusses growing opportunities for synergistically advancing soil science, hydrology, and geosciences. This discussion is timely because soil science programs worldwide have struggled to survive, the hydrology community is becoming united because of the current global concern for fresh water, and the geosciences community has embraced an expanded vision of its role and societal relevance. Specific objectives of this paper include: (1) a clarification on the basic ideas of the CZ and hydropedology, and their relations to relevant disciplines; (2) a suggestion of a broadened perspective for future soil science advancement; (3) a highlight of fundamental

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characteristics and research opportunities of the CZ and hydropedology; and (4) a discussion of possible ways for advancing CZ science and hydropedology. This paper focuses on physical and hydrological aspects of the CZ, with hydropedology as an example (among many other disciplines) to illustrate the opportunity and the need for integrated, multiscale, and synergistic efforts in understanding, managing, and sustaining the whole CZ. Coupling between physical/hydrologic and biogeochemical/ecological processes is an emerging topic, which has been recently reviewed by McClain et al. (2003), Lohse et al. (2009), and others.

2 Critical Zone Science

2.1 History of the Concept of the Critical Zone and Its Current Meaning and Utility

The generic term of “critical zone” first appeared a century ago in a German article by physical chemist D.E. Tsakalotos (1909), referring to the zone of a binary mixture of two fluids. In 1962, American mineralogist E.N. Cameron called a geological formation (the Bushveld Complex in South Africa) a “critical zone.” As of March 15, 2009, based on the *Science Citation Index Expanded*, a total of 314 publications have used the term “critical zone” to refer to wide-ranging things: from geological formation where precious metals (such as platinum and gold) can be mined (Wilhelm et al., 1997) to pipe corrosion in soil within ground water fluctuation zone (Decker et al., 2008); from the rhizosphere where soil and roots have close interaction (Ryan et al., 2001) to transitional zones in alluvial coastal plain rivers important for water resource management (Phillips and Slattery, 2008); from body ventricular slow conduction area with electrophysiological limitations (Elsherif et al., 1990) to local cold regions of ice-structure interaction where intense pressures occur over short time leading to ice failure (Johnston et al., 1998). The majority of these 314 papers were in the subject areas of geosciences (46%) and minerals/energy (41%). Only 15 of them used the term of “critical zone” in relation to soils, and 15 papers referred it to water related issues.

In 2001, the NRC specifically defined the “Critical Zone” (note capitalized letters). This CZ concept was suggested by a subgroup of the NRC Committee on Basic Research Opportunities in the Earth Sciences (Wilding, 2006), consisting of a sedimentologist (Gail Ashley), a pedologist (Larry Wilding), and a hydrologist (Stephen Burges). Since then, enthusiasm and skepticism

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have surfaced in scientific communities regarding the meaning and utility of this concept. An attempt is thus made in the following to clarify some related issues or concepts:

(1) Many people thought that the CZ is (nearly) the same as soils. However, the CZ is much broader than soils (see Figs. 1 and 2). It is true that the CZ encompasses the entire pedosphere—the only sphere in the Earth system that is wholly included in the CZ. However, if the CZ is limited to just soils (this perspective is labeled here as "inward" contraction; see Fig. 2), then it loses the integrating and unifying power of the CZ. We should, instead, promote a broadened perspective on soils (this is labeled here as "outward" growth; see Fig. 2), thereby permitting an inclusive vision for future soil science. This "outward" growth view is consistent with the soil's recognized "7 + 1" functions as depicted in Fig. 2 (Lin, 2005) and seven soil functions identified by the EU Soil Protection Strategy (Commission of the European Communities, 2006; Bouma, 2009). Soil scientists, while focusing on soil processes, can then see their knowledge in a much broader context.

(2) Some have used the term CZ as synonymous with a common geological term "regolith" (defined as "*the fragmental and unconsolidated rock material, whether residual or transported, that nearly everywhere forms the surface of the land and overlies the bedrock. It includes rock debris of all kinds – volcanic ash, glacial drift, alluvium, loess, vegetal accumulations, and soil*;" Bates and Jackson, 1987). Regolith is synonymous with mantle or overburden, and is equivalent to the broader concept of soil that includes O-A-E-B-C horizons (the C horizon is often called saprolite; see Fig. 1). The classical narrower concept of soil has been driven by agriculture-centric conception of the soil as a medium for plant growth, which includes only the A-B horizons (called solum, generally < 1-2 m deep; see Fig. 1). The CZ, as defined by the NRC (2001), integrates above-regolith vegetation and below-regolith fresh bedrock or sediments that interact with fluctuating ground water.

(3) Some people have questioned the utility of the CZ concept because of its imprecise lower boundary and highly variable thickness from place or place. On the contrary, this is precisely the benefit for using the CZ concept as it will force us to better define the variable and dynamic lower boundary of the active water cycle, especially under unsaturated flow conditions. Currently we do not know exactly where the active water flow ceases in the subsurface in different ecosystems and geographic regions, yet such an understanding is important as this

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demarcation influences the annual, decadal, and century hydrologic cycles. Hydrologic and biogeochemical models have often been forced to make assumptions about the lower boundary of the active water cycle (such as impermeable bedrock or an artificial 2 m cut-off for soil depth). But the diffuse lower boundary of the CZ may extend to a kilometer or more beneath a fractured bedrock and the volume of water stored in this zone may be an order of magnitude larger than the combined volume of water in all rivers and lakes (NRC, 1991, 2001).

(4) Many researchers believe that the CZ concept is useful because it is inherently process-oriented and is a unifying framework that accommodates the hydrologic cycle, the geochemical cycle, the carbon cycle, the nutrient cycle, gas exchange (major and trace gases), erosion and deposition, weathering (chemical and physical), lithification (diagenesis), soil formation and evolution (pedogenesis), life processes (macro- and microbial communities, including plants and animals), and human impacts (land use and land management). The timescales included in the CZ concept range from seconds to eons and its spatial scales are enormous (from atomic to global) (NRC, 2001). As indicated by the NRC (2001), the rapidly expanding needs for a sustainable society give special urgency to understanding the processes that operate within the complex CZ. Some pressing scientific issues that involve the CZ include global climate change, terrestrial carbon cycle, life-water-mineral interactions, land-ocean interface, and earth history (NRC, 2001).

2.2 General Characteristics of the Critical Zone

The CZ is perhaps "*the most heterogeneous and complex region of the Earth*" (NRC, 2001) and has been recognized as "*the most complicated biomaterials on the planet*" (Young and Crawford, 2004; NRC, 2009). Despite its extreme complexity and dynamics, however, some general characteristics of the CZ can be identified (Fig. 3), which can help its holistic understanding:

1. The CZ is evolutionary. Changes in the CZ are generally irreversible and cumulative, which may be introduced by either slow, more gradual processes or extreme, abrupt changes. Increasingly, human alternations to the CZ have become pervasive and long-lasting.
2. The CZ is a coupled system. Cycles of geological and biological processes over vastly different spatial and temporal scales is a key to understanding the CZ, which involves all spheres of the Earth system.

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3. Vertically, the CZ has layers. The interfaces between layers are critical controls of the CZ's response and feedback times to aboveground changes in climate and land use.
4. Horizontally, the CZ is highly heterogeneous. Hierarchical organization of ubiquitous heterogeneity in the CZ exhibits gaps between conceptualized scales. Meanwhile, networks embedded in land mosaics are common features that may shed light on the efficient transfer of energy, mass, entropy, and information in the CZ.

Each of the above characteristics is further elaborated in the following. Together, these characteristics could help forge a holistic and evolutionary worldview of the CZ.

2.2.1 Irreversible Evolution

Natural systems are open systems in terms of energy, because solar energy enters freely and heat energy goes back into space. Such thermodynamically open and dissipative systems have driven the evolution and functioning of the CZ (Lin, 2010b). As dictated by the second law of thermodynamics, nature has a tendency to go toward disorder, with spontaneous increase in entropy (which can be interpreted as an index of system's disorder; Boltzmann, 1896). In the meantime, Prigogine's (1977) theory of dissipative structures suggests that, as energy dissipates, complex structures are formed through the system's self-organization (meaning a process of attraction and repulsion in which the internal organization of a system increases in complexity without being guided by an outside source). A balance exists between two opposing tendencies: moving away from thermodynamic equilibrium (via organization) vs. slippage back towards it (through dissipation) (Ulanowicz, 2009).

Time irreversibility is essential to the evolution of the CZ. Unlike space, time cannot be reversed because time always moves forward in one direction. Many physical, chemical, and biological changes occurred in nature are also irreversible (Prigogine, 1977), because energy dissipation results in heat lose that cannot be totally converted back to work should the process be reversed. Consequently, the exact same conditions can not occur again in the natural world (Tiezzi, 2006). In particular, living creatures and ecosystems obey the laws of biological evolution: at any time they are different from what they were an instant before (Tiezzi, 2006). This is the essence of life. Time evolution also has accumulative and memory effects. In fact, life is only possible if it does not start from zero for every new generation; rather, mechanisms to store information gained, e.g., through genes, make the evolution of life possible (Jørgensen, 2006). Over time,

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(1) *Tectonics* driven by energy in the mantle, which modifies the Earth surface by geological processes such as magmatism, faulting, uplift, erosion, and subsidence, leading to the creation of basic landforms over the geological timescale; ¶
(2) *Weathering* driven by the dynamics of the atmosphere, hydrosphere, and biosphere, which controls soil formation and evolution from rocks or sediments, water quality, ecological functions, and biogeochemical cycles over generally long timescale;¶
(3) *Fluid transport* driven by energy or mass gradients (e.g., pressure, temperature, and concentration), which shapes the landscape and the distribution of water, soil, vegetation, and microbes, with water being the primary conduit;¶
(4) *Biological activity* driven by the need for life-sustaining resources (water, nutrients, air, and light), which controls the biogeochemical cycling and ecological functioning among soil, rock, air, and water, and which greatly accelerates weathering and spatio-temporal variability in the CZ over much shorter timescale as compared to geological processes;¶
(5) *Human activity* driven by socio-economic, political, and personal ... [20]

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evolution progresses towards more and more complex and organized systems (Tiezzi, 2006). Many ordered systems exhibit emergent properties (i.e., properties that a system possesses in addition to the sum of properties of its components, that is, the whole is more than the sum of its parts).

Dissipative structure, along with information stored and aesthetics (quality) accumulated over time, play a fundamental role in natural evolutionary process (Tiezzi, 2006). Both energy and mass conservation and entropy and information accumulation are at work simultaneously in the evolution of the CZ (Fig. 3) (Lin, 2010b). Therefore, cross fertilization between evolutionary and conservative principles is essential to understanding physical vs. biological laws that govern the structure and function of the CZ (Lin, 2010b).

The CZ is also awash in events that occur once and never again. Jørgensen et al. (2007) and Ulanowicz (2009) suggested that singular events in nature are not rare; rather they are legion and can occur everywhere, all the time and at all scales. Such a common phenomenon is probably linked to the irreversible nature of time and dissipative processes described above. Furthermore, the duality of chance and choice is characteristic of evolution of natural systems (Monod, 1971; Tiezzi, 2006; Rinaldo et al., 2006). This duality leads to complex systems that disobey linear deterministic laws; instead, the combination of chance and selection involved in evolution gives rise to unexpected structures and events, the properties of which can be quite different from those of the underlying elementary laws and may take the form of abrupt transitions, a multiplicity of states, new patterns, or irregular and unpredictable outcomes, which is referred to as deterministic chaos (Nicolis, 1995; Tiezzi, 2006).

Increasingly, human impacts on the CZ have become fundamental (Richter, 2007; Richter and Mobley, 2009). Besides the forcing of tectonics, weathering, fluid transport, and biological activities (NRC, 2001), the Anthropocene has been increasingly recognized, which is "*a new geological epoch in which humankind has emerged as a globally significant, and potentially intelligent, force capable of reshaping the face of the planet*" (Clark et al., 2004). Soil thickness in the CZ, for example, illustrates well the accelerated changes caused by humans: average rate of soil formation from bedrock weathering has been estimated by many as 1 mm per 1,000 years or less, while the rate of soil erosion has reached an average rate of 10-20 mm per 1,000 years in many areas because of human activities (McKenzie et al., 2004; Brantley et al., 2006). Such an

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imbalance between the slow production of new soil (which is generally infertile subsoil above the bedrock) and the accelerated lose of fertile topsoil has severe negative and irreversible consequences for the sustainability of the CZ.

2.2.2 Coupled Cycling

In terms of physical matters—soil, water, air, and other resources—the Earth is essentially a closed system from a global perspective. The only exceptions are the slow escape of lightweight gases (such as hydrogen) from the atmosphere into space and the input of frequent but tiny meteors and cosmic and meteoric dusts (Christopherson, 2007). Thus, the Earth's physical materials are finite (for all practical purposes) and hence tend to depend on cycling for continued use. This implies that, no matter how numerous and daring human technological reorganizations or transformations of matters may become, the material base of the CZ is fixed and limited.

The CZ has two overarching cycles that are vastly different in space and time scales: the geological cycle (dubbed "big" cycle) and the biological cycle (dubbed "small" cycle) (Fig. 4). It is the reconciliation of these two cycles that is critical for understanding the CZ's complex evolution and dynamic functions. *The geological cycle* refers to the weathering of rocks, the erosion, transport, and deposition of weathered products that eventually end up in oceans as sediments, and then are lithified and uplifted back to the land by tectonic or volcanic activities. This cycle, occurring over the geological timescale and often a large area, is composed of three major sub-cycles—tectonic, lithologic, and hydrologic (Fig. 4). The tectonic cycle brings heat energy and new materials to the surface and recycles materials, creating movement and deformation of the crust. The rock (or rock-soil) cycle produces igneous, metamorphic, and sedimentary rocks in the crust, including soil cycle as rocks weather into soils and soils return to rocks over the geological timescale. At this geological timescale, the hydrologic cycle processes materials with the physical and chemical actions of water, ice, and wind.

The biological cycle refers to the production and consumption of food and energy in an ecosystem and the accumulation and decomposition of organic materials in soils. The flow of energy, the cycling of nutrients, and trophic relations determine the nature of an ecosystem. Compared to the geological cycle, the biological cycle occurs over a much shorter timescale and often a smaller area. Three principle sub-cycles are involved—ecological, biogeochemical, and

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hydrologic (Fig. 4). The ecological (or life) cycle generates biomass through producers such as plants, reaching consumers and eventually detritivores through the food chain. Soils support vast communities of microorganisms that decompose organic matter and re-circulate elements in the biosphere (Fig. 1). Anthropologic impacts may be considered as part of the ecological cycle; alternatively, human activity can be elevated to a separate cycle because of its increasingly dominant impacts on the biological cycle. The biogeochemical (or elemental) cycle, combining biotic and abiotic processes, redistributes elements and materials through liquid (e.g., water), solid (e.g., sediments), and gas (e.g., air). At the biological timescale, the hydrologic cycle transports organic and inorganic materials and energy throughout the CZ.

Fluid transport is involved in both the geological and biological cycles, since water is the key conduit for mass and energy transfer. Life on Earth as we know it would be impossible without liquid water. The biosphere is ultimately what ties the major systems of the Earth together and drives them far out of thermodynamic equilibrium (Jacobson et al., 2000). The cyclic approach mimics the coupled nature of the CZ, e.g., biogeochemical cycle is inseparable from the hydrologic cycle, and together they determine the ecological cycle. However, traditional discipline-limited and individual component-based efforts have plagued our understanding of coupled CZ system. It is hoped that the emerging CZ science can significantly advance holistic and evolutionary worldview of complex coupled systems.

The cyclic approach allows conceptual simplification of materials movement and their couplings to the environmental factors. Using the most basic description of the cyclic processes, mathematical models have been used to describe and predict the distribution of important elements of interest, such as water, sediment, carbon, nitrogen, and others (Jacobson et al., 2000). Many computer models, especially those of the global scale, use this approach. In many cases, the details of the distribution of an element within each of reservoirs are disregarded, and for the most simplified calculations, the amounts of material in each reservoir are assumed to be at steady-state. This allows an element budget to be defined for the entire cycle. Such a steady-state budget-based approach, however, has limitations because it provides little or no insight into what goes on inside each reservoir or the nature of the fluxes between reservoirs (Jacobson et al., 2000). The average-based analysis also does not consider spatial and temporal variation, and thereby could give a false impression of certainty.

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2.2.3 Interactive Layers

The Earth is a vertically layered system: from outer atmosphere down to inner core, different layers of materials with vastly different thicknesses and characteristics are evident (Figs. 1 and 2). The CZ consists of the aboveground vegetation zone, the belowground root zone, the deep vadose zone, and the saturated ground water zone, with each layer having various sub-layers. Because of this layering characteristic and a generally increasing trend in density with depth (with exceptions), plus increasing distance to energy input at the soil surface and the dampening effect of state variables with depth (Vogel, 2009), there is an overall trend of increasing characteristic response time (i.e., time period needed to reach a quasi-steady state with the environment) to external perturbations when moving from the atmosphere, down to the hydrosphere, biosphere, pedosphere, and further down to the lithosphere (Arnold et al., 1990). Conversely, the time period needed to feedback to climate and land use changes generally decreases when moving up from the deep underground zone to the shallow subsurface zone to the surface zone and to the aboveground zone.

Key interfaces in the CZ include the land surface-atmosphere interface, the soil-vegetation interface, the vadose zone-ground water interface, the surface water-ground water interface, the soil-stream interface, and the soil-bedrock interface. These interfaces are unique and important controls of the landscape-soil-water-ecosystem-climate relationships. For example, fluctuating ground water has a significant influence on the nature and properties of the lower part of soil profiles (Jenny, 1941; Narasimhan, 2005). Changing ground water levels also has effects on the energy balance at the soil surface and the susceptibility of a region to drought (Maxwell and Kollet, 2008). The NRC (2004) highlighted the importance of ground water fluxes across interfaces when estimating recharge and discharge to aquifers. However, many challenges remain in understanding and measuring dynamic interchanges among the water reservoirs of atmosphere, surface, and subsurface, especially with the subsurface. Sophocleous (2002) reviewed recent advances in ground water and surface water interactions, and pointed out that most models today are not well equipped to deal with local phenomena related to flow near domain boundaries (i.e., interfaces), and yet the upper few centimeters of sediments beneath nearly all surface water bodies (hyporheic zone) have a profound effect on the chemistry of the water interchanges. Pielke et al. (1998) showed convincing evidence that terrestrial ecosystems

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The intertwining relationships of climate, hydrology, biology, lithology, topography, chronology, and anthropogenic impacts pose challenges to the independence assumption made in Jenny's (1941) soil-forming theory, although in some areas one of the factors may dominate (thus permitting r ... [26]

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significantly interact with atmospheric processes, and thus they are as important as changes in atmospheric dynamics and composition, ocean circulation, ice sheet extent, and orbit perturbations in the studies of past and future climate change.

Within a soil profile, important interfaces also exist, including the soil horizon interface, the soil-root interface, the macropore-matrix interface, the microbe-aggregate interface, the water-air interface, and the soil-water table interface, all of which are places where important interactions occur. For instance, soil chemical reactions generally occur at various interfaces, including the equilibrium and kinetic processes of dissolution/precipitation, adsorption/desorption, oxidation/reduction, and polymerization/biodegradation. As another example, illuviation leads to various coatings on soil interfaces, such as clay films, carbonates, or redox features at the surfaces of soil particles or aggregates. The fact that natural soils are layered also has significant implications for water flow and chemical transport. Interfaces between soil layers often slow down vertical water percolation and promote lateral flow, especially in sloping landscape with an underlying water-restricting layer. Interfaces between horizons with different textures or structures often trigger preferential flow, and thus can impact the scaling of flow and transport processes. These interfaces are important in defining at what depth a soil profile will begin to saturate and the runoff pattern for a catchment (Lin et al., 2008b).

2.2.4 Hierarchical Heterogeneity

Ubiquitous heterogeneity and scale bridging underlie nearly all of the CZ studies. Heterogeneity here differs from randomness: the former is associated with order while the later is linked to disorder. Currently no single theory emerges that is ideal for spatial aggregation (or upscaling), disaggregation (or downscaling), and temporal inference (or prediction) of diverse processes occurred in the CZ. Despite this, certain causes of heterogeneity in the CZ can be identified, and possible ways of bridging scales should be continuously explored.

Based on Prigogine's (1977) theory, a dissipative system in nature is characterized by the spontaneous appearance of symmetry breaking (leading to anisotropy) and the formation of complex structures (leading to heterogeneity). Patterns of heterogeneity are the diagrams of processes (Bell, 1999). Soil-forming theory provides a useful framework for understanding the mechanisms leading to soil heterogeneity, where systematic (ordered) variation can be identified by environmental controls (such as climate, organisms, landform, and parent material), whereas

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random (disordered) variation is stochastic. Differentiation of systematic vs. random variations allows a focus on the proportion of the CZ variability that can be related to known causes.

Patterns in the landscape, however, are often unclear because they comprise many layers of elements, with each element having its own heterogeneity. These elements are often intricately woven together due to the interactions of different processes occurred in the CZ. Bell (1999) suggested that it is possible to consider landscapes as complexes of networks and mosaics. The networks are patterns of linear-oriented features, such as the meandering and branching systems that run through and between the elements that produce the mosaics. Mosaic patterns can be found over a wide range of spatial scales, from the submicroscopic soil matrix to the entire pedosphere. Mosaics arise because of uneven and dynamic energy inputs into the open system of the CZ, leading to structural and compositional heterogeneity at all scales. The mosaic patterns can be determined by mechanisms characteristic of underlying processes, including (Bell, 1999):

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s…not …all the… at work…of the soil s…spatial, structura…l,…, and temporal…various …which may be grouped into three main ones ... [36]

- *Inherent processes*: the substrate heterogeneity beneath the land mosaic is dependent on the processes of geology, geomorphology, pedology, and hydrology, interacting with climate and biota;
- *Extrinsic processes*: the effect of natural disturbances (such as fires, hurricanes, insect pests, and diseases) to the biota that colonize and grow on the variable substrate;
- *Anthropomorphic processes*: human activities ranging from land use/land cover change to modification of landform, urbanization, and interference with the climate.

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There is an apparent hierarchy in the heterogeneity of soils and the CZ (Fig. 5). Patterns may emerge (emergent properties) at a large scale from the complex interactions of a large number of different elements at a smaller scale. The dominant process and controlling factor may also change in a hierarchical manner as scale changes. Therefore hierarchical frameworks have been utilized by geoscientists, soil scientists, and hydrologists as a means for organizing natural systems from the pore scale to the global scale (Fig. 5). However, a quantitative and operational hierarchy that can be integrated into models of scaling, flow, and rate processes remains a major research challenge today, where gaps exist in between hierarchical levels (Fig. 5). The present inability to adequately characterize subsurface heterogeneity exacerbates the scaling problem and leads to significant uncertainties in data interpretations and model predictions for the CZ (Sophocleous, 2002).

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a strong…ical structure to …most natural and human patterns and processes…the as scale changes …conceptualized … including …description …of such …ical systems… …could …flow, …is still lacking…. It is possible that heterogeneity is huge and the numbers of possible patterns may be limitless at a fine level of detail while the possible range of patterns may be remarkably limited as spatial dimensions increase (Stevens, 1974; Bell, 1999). ... [40]

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von Bertalanffy (1968) indicated that there is a general lack of appropriate scientific means for dealing with systems between extremes—systems of so-called medium numbers (Fig. 5). Weinberg (1975) described three types of systems that require different thinking:

- Systems of "*organized simplicity*" (Region I in Fig. 5): this is the region of machines, or mechanisms. This region has small populations with a great deal of structure, which could be treated analytically;
- Systems of "*unorganized complexity*" (Region II in Fig. 5): this is the region of large populations, where statistical mechanics applies. This region is complex, but yet sufficiently random so that it is sufficiently regular to be studied statistically. Randomness (or structureless) is the property that makes statistics work here;
- Systems of "*organized complexity*" (Region III in Fig. 5): this is the region too complex for analysis and too organized for statistics. This is the region of systems with medium numbers, with essential failure of the two classical methods (analytical and statistical treatments).

As remote sensing techniques for estimating large-area soil, hydrologic, and ecosystem patterns, and *in situ* point-based measurements continue to be developed, bridging multiple scales from points to watersheds and to the globe becomes essential. While advanced imaging, spectroscopic, and other technologies become widely used at the pore or even molecular level, and computer modeling together with remote sensing and other tools are increasingly used at the global level, what is often missing and urgently needed is improved tools and techniques for characterizing the subsurface at the intermediate scale (e.g., from the pedon to the hillslope and catchment scales; Fig. 5). This is essentially the region of medium number systems that calls for a new way of thinking and treatment.

3 Hydropedology

3.1 Fundamentals of Hydropedology

Hydrogeosciences have encountered a new intellectual paradigm that emphasizes connections between the hydrosphere and other components of the Earth system. While hydrogeology, hydrometeorology, and ecohydrology are now well recognized, an important missing piece of the

Deleted: A conceptual framework has been used to understand the *magnitude* of land surface/subsurface variability as a function of five space-time factors (Lin et al., 2005b): spatial extent or area size, spatial resolution or map scale, spatial location or geographic region, specific property or process, and absolute or relative age. Broadly speaking, it is expected that as spatial extent, spatial resolution, or time scale increase, the magnitude of overall soil variability should increase, reaching a possible maximum and then starting to stabilize or decrease as space or time dimensions continue to increase; however, the mode and magnitude of such changes would depend on the landscape (i.e., spatial location) and which soil type or specific soil property/process is of concern. Numerous publications have provided evidence that supports such a general conceptualization (e.g., Wilding and Drees, 1983; Burrough, 1993; Heuvelink and Webster, 2001). A significant need, however, still exists for explicit quantification of the complexity, diversity, and interactions related to such a conceptual framework.¶
While spatial variance is often attributed to spatial autocorrelation in geostatistics, the *causes or mechanisms* of heterogeneity are important for understanding why field variation exists and how that changes with scale. Systematic (ordered) variation is controlled by the environmental gradients (such as landforms, geomorphic elements, soil-forming factors, and land management) which can be identified; while random (disordered) variat ... [41]

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puzzle is the interface between the hydrosphere and the pedosphere. Hydropedology addresses this interface, and seeks to answer the following two basic questions (Lin et al., 2008a, b):

(1) How do soil architecture and the distribution of soils over the landscape exert a first-order control on hydrologic processes (and associated biogeochemical and ecological dynamics) across spatio-temporal scales?

(2) How does landscape water (and the associated transport of energy, sediment, chemicals, and biomaterials by flowing water) influence soil genesis, evolution, variability, and functions?

Landscape water here encompasses the source, storage, availability, flux, pathway, residence time, and spatio-temporal distribution of water in the variably-unsaturated near-surface environment (Lin et al., 2006a). While source, storage, availability, and flux of water have been studied extensively in the past, attention to flow pathways (especially flow networks), residence time (age of water), and spatio-temporal pattern of flow dynamics (and its underlying organizing principles) has been much less (McDonnell et al., 2007).

Fundamental scientific issues of hydropedology, at this point of its development, may be considered under four headings (Lin et al., 2005):

(1) *Soil structure and horizonation* determine *in situ* characteristics of soil water flow and chemical transport. Hydropedology emphasizes soil architecture and its quantitative links to preferential flow across scales;

(2) *Soil catena and distribution pattern* are a first "control" of water movement over the landscape. Hydropedology focuses on quantitative soil-landscape relationships and their impacts on hydrologic, biogeochemical, and ecological processes;

(3) *Soil morphology and pedogenesis* are signatures of soil hydrology and records of soil changes over time. Hydropedology emphasizes quantitative soil hydromorphology and the values of soil environmental records;

(4) *Soil functions and maps* are "carriers" of soil quality and soil-landscape heterogeneity. Hydropedology promotes quantitative functional soil units, soil functional cataloging, and reliable and precision soil mapping for diverse applications.

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Lin et al. (2005) have provided a comprehensive review to the above fundamental issues. In the following, only a brief update since then is provided to exemplify the contributions from hydropedology to the needed integrated, interdisciplinary, and multiscale studies of the CZ.

3.1.1 Soil structure and horizonation: their impacts on preferential flow

Natural soils generally contain multiple horizons, and each horizon is structured to various degrees (Figs. 6 and 7). *Soil architecture* is used broadly here to encompass three parts: (1) solid components, including soil matrix (represented by soil texture and its microfabic) and soil aggregation (represented by the type, quantity, and size distribution of peds, and aggregate stability); (2) pore space, including the size distribution, connectivity, tortuosity, density, and morphology of various pores; and (3) interfaces between solid components and the pore space, such as coatings on peds or pores, and the interfaces of macropore-matrix, soil-root, microbe-aggregate, and in between horizons.

Because of heterogeneous soil architecture, variability in energy and mass inputs to soils, and diversity in soil hydrologic processes and biological activities, preferential flow can occur in practically all natural soils and landscapes (Fig. 6) (Lin, 2010a). As Clothier et al. (2008) summarized well, preferential flow can occur spatially at the pore scale of spatial order 10^{-3} m, at the core scale (10^{-1} m), in pedons (10^{0} m), down hillslopes (10^{1}-10^{3} m), through catchments (10^{4}-10^{5} m), and across large regions of $\geq 10^{6}$ m. Time-wise, preferential flow can operate during fluid flows at the temporal order of 10^{0}-10^{1} s, during hydrological events 10^{0}-10^{2} hours, throughout seasonal changes 10^{0} year, and across inter-annual variations of 10^{1} years.

Based on several theoretical considerations and numerous published evidence, Lin (2010a) has attempted to justify the likely universality of preferential flow in natural soils—meaning that the potential for preferential flow occurrence is anywhere in nature, although the actual occurrence of preferential flow will depend on local conditions (Lin and Zhou, 2008). Lin (2010a) also showed that networks are abundant in soils, such as root branching networks, mycorrhizal mycelial networks, animal borrowing networks, crack and fissure networks, artificial subsurface drainage networks, and pore networks between soil particles and aggregates. These networks provide preferential flow conduits, which in return reinforces or modifies the existing networks.

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Deleted: is the rule; whereas the existence of a macroscopic homogeneity is the exception (Bouma and Dekker, 1978; Hoogmoed and Bouma, 1980; Vogel and Roth, 2003). It has been said that a crushed or pulverized sample of the soil is related to the soil formed by nature like a pile of debris is to a demolished building (Kubiena, 1938). Lin (2007) also suggested that a crushed soil sample is as akin to a natural soil profile as a package of ground beef is to a living cow. The fundamental difference between *in situ* soils in the landscape and disturbed soil materials in the laboratory lies in "soil architecture." The soil is a living entity, with many dynamic forces acting upon it so its internal architecture forms and evolves over time to serve multiple functions. A new era of soils research should rely on soil architecture—built upon the past "texture-centered" ... [54]

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3.1.2 Soil catena and distribution: their controls on landscape water movement

Sommer and Schlichting (1997) suggested that an integration of three different approaches to study soil distribution—geomorphic/stratigraphic, hydrologic, and pedologic approaches—is the most promising way forward toward a four-dimensional understanding of soil-landscape relationships. Two types of soil distribution patterns can be differentiated in terms of their controls and scales: (1) At the hillslope and landscape scales, soil patterns are heterogeneous due to factors that vary over short distances such as topography and parent materials (the site factors of soil formation). This soil pattern is often referred to as a "soilscape," i.e., the pedologic portion of the landscape (Hole, 1985; Buol et al., 2003), which includes catenas and other more localized soil distribution pattern such as gleization and Histosols; and (2) At the regional and global scales, zonal soil patterns are expressed by a gradual change in soils over large areas, resulting from climatic and vegetative gradients (the flux factors of soil formation). These physiographically-oriented soil patterns are recognized in the U.S. as Major Land Resources Areas (defined as geographically associated land resource units that are characterized by a particular pattern of soils, water, climate, and land use; USDA-NRCS, 2006).

Catenas in different climatic and physiographic regions may exhibit markedly different relationships between soil and hydrologic properties (Schaetzl and Anderson, 2005; Lin et al., 2006b; Wilcox et al., 2007; Lin et al., 2008b). Drainage condition, water table depth, and fluxes of water, solutes, and sediments typically differ in soils along a catena (Fig. 8). However, contrasting hydrology and soil morphology (e.g., Fig. 8a vs. 8b) cannot be explained by simple catenary model where surface topography controls hydrological regimes (Fig. 8a); instead, the topography of the underlying weathered rock substrates with low-permeability causes subsurface distribution patterns of soil and hydrology in Fig. 8b (Coventry, 1982). The soil-bedrock interface and bedrock topography have now been recognized as important to subsurface stormflow in hillslopes (e.g., Freer et al., 2002; Tromp Van Meerveld and McDonnell, 2006).

3.1.3 Soil morphology and pedogenesis: their records of soil hydrologic change

Soil macro- and micro-morphology have long been used to infer soil moisture regimes, hydraulic and biogeochemical properties, and landscape processes (Lilly and Lin, 2004; Lin et al., 2008b). In particular, water-dominated pedogenesis leads to so-called soil hydromorphology—a result of

Deleted: In the U.S. *Soil Taxonomy*, various diagnostic surface and subsurface horizons have been identified (Soil Survey Staff, 2006). The presence or absence of these horizons plays the major role in determining in which class a soil falls in *Soil Taxonomy*. Numerous water-restricting subsurface soil horizons (such as fragipan, duripan, glacic, ortstein, permafrost, petrocalcic, petrogypsic, and placic horizons) and features (including aquic conditions, cryoturbation, densic contact, fragic soil properties, gelic materials, lamellae, lithic contact, lithologic discontinuities, petroferric contact, and plinthite) are important to hydrdologic and biogeochemical cycles (Soil Survey Staff, 2006). Other subsoil horizons may also act as an aquitard or aquiclude to downward moving water (Fig. 7), ultimately resulting in a seasonal perched water table and water moving laterally within the soil as subsurface throughflow (e.g., Kemp et al., 1998; Gburek et al., 2006). Such subso ... [57]

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permanent or temporary state of water saturation in the soil associated with conditions of reduction (predominantly the accumulation or loss of Fe, Mn, S, or C compounds) (USDA-NRCS, 1998). The spatial relationships of redox depletions and redox concentrations may be used to interpret the pattern of water and air movement in soils (Vepraskas, 1992). The presence of organic matter and a suitable temperature and pH are generally required for hydromorphism to occur. Such biochemical processes might have implications for finding possible clues to life on Mars—if Martian soil hydromorphism or paleo-hydromorphism (formed in ancient hydromorphic condition) can be observed. This is because biological activity is often involved in soil hydromorphism on Earth, while diagenetic hydromorphism is also considerably accelerated by microorganisms.

Hydrology has been suggested as a possible integrating factor of soil formation and a main driving force of soil dynamics (Lin et al., 2005). This is because all of the five natural soil-forming factors affect and are affected by hydrology. Water from precipitation is a primary requisite for parent material weathering and soil development. To reach a highly developed stage, sufficient amount of water must not only enter the profile and participate in weathering reactions, but also percolate through the profile and translocate weathering products (such as solutes and clays). Therefore, the characteristics of a soil profile may reflect the total amount of water that has passed through it over time, which has potential merits in quantifying pedogenesis. To illustrate, Fig. 7 shows a general sequence of soil development from a young Entisol to a highly-weathered Ultisol: as soil age increases, soil thickness increases as weathering increases, but soil saturated hydraulic conductivity would first increase and then decrease in the subsoil. As more structural (organized) heterogeneity develops through pedogenesis, more preferential flow (vertically or laterally or both) would likely occur (Lin, 2010a).

3.1.4 Soil functions and maps: their connections to soil hydraulic properties

Soil quality is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (SSSA, 2009). Soil carbon content is widely recognized as a major factor in the overall quality and functions of soils, but human land use/management has significant impacts on soil carbon and overall soil quality. The concepts of "*genoform*" (for genetically defined soil series) and "*phenoform*" (for soil types resulting from a particular form of management in a given

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genoform) (Droogers and Bouma, 1997) offers a possible means to incorporate management effects into hydropedologic characterizations of soil functions, which can enhance pedotransfer functions that involve soil series and land use as carriers of soil hydraulic properties.

Soil map is a common way to portray soil heterogeneity and to provide soil input parameters to models. However, virtually every delineation of a soil map unit includes other soil components or miscellaneous areas that are not identified in the name of a map unit because of limitations in map scale and other factors (Soil Survey Division Staff, 1993). Quantification of map unit purity for different scales of soil maps is a needed area of improvement in modern soil surveys (Arnold and Wilding, 1991). Precision soil mapping is of increasing demand for site-specific applications of soils information (such as precision agriculture and landscape hydrology). Modern soil maps also need improvements for functional characterizations rather than classical general land use planning. Soil maps can no longer be static documents; rather, derivative and dynamic maps, tailored for a specific function or purpose, must be generated and updated on a regular basis. Making connections between hydropedology and digital soil mapping is a promising research area, which will improve the connection between soil mapping and modeling.

3.2 Characteristics of Hydropedology and Its Link to Critical Zone Science

Two general characteristics of hydropedology are discussed below, which are linked to the two basic questions of hydropedology as described in Section 3.1.

First, hydropedology emphasizes *in situ* soils in the landscape, where distinct pedogenic features (e.g., aggregation, horizonation, and redox features) and soil-landscape relationships (e.g., catena, soil distribution patterns, and soil map units) are essential in understanding interactive pedologic and hydrologic processes. Developing quantitative relationships between complex natural soil architecture and soil hydrologic functions across scales is an important research area of hydropedology. Three related key aspects are noted here:

- Hydropedology calls for a new era of soils research that is bases on soil architecture (rather than soil texture) so that the prediction of flow (and reaction) pathways, patterns, and residence times can be made more realistically. This requires innovative techniques for improved quantification soil architecture at different scales, especially *in situ*

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noninvasively, and then linking such soil architectural parameters to field-measured soil hydraulic properties;

- Hydropedology considers the soil as a "living" entity in the landscape, rather than a "dead" material. As Kubiena (1938) pointed out, a crushed or pulverized sample of the soil is related to the soil formed by nature like a pile of debris is to a demolished building. Lin (2007) also suggested that a crushed soil sample is as akin to a natural soil profile as a package of ground beef is to a living cow;
- Hydropedology attempts to link the form and function of a soil system across scales (Lin et al., 2006a), rather than mapping soils without considering soil functions or modeling soils without incorporating soil architecture and soil-landscape patterns.

Jenny (1941) noted, "*The goal of soil geographer is the assemblage of soil knowledge in the form of a map. In contrast, the goal of the 'functionalist' is the assemblage of soil knowledge in the form of a curve or an equation… Clearly, it is the union of the geographic and the functional method that provides the most effective means of pedological research.*" Such a union of soil maps and soil functions is what hydropedology hopes to accomplish, in quantitative ways.

Second, hydropedology deals with the variably unsaturated or saturated zone in the near-surface environment, including the shallow root zone, deep vadose zone, temporally-saturated soil zone, capillary fringe, wetlands, and subaqueous soils (soils that form in sediment found in shallow permanently flooded environments such as in an estuary) (Demas and Rabenhorst, 2001). Three related key aspects are noted here:

- Hydrology has the potential to be an integrating factor for quantifying soil formation and evolution as well as for understanding soil changes (Lin et al., 2005), hence a focus on water may improve means for quantifying dynamic soil functions;
- New ways of characterizing and mapping soils may be linked to hydrology, such as delineating hydropedologic functional units that are soil-landscape units with similar pedologic and hydrologic functions (Lin et al., 2008b);
- The interpretation and quantification of soils as historical records of environmental changes may be significantly improved if hydrologic data are considered simultaneously.

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This is demonstrated in some studies of palesols and palehydrology (Ashley and Driese, 2000)

Hydropedology is closely linked to CZ science because of the key roles that soil and water play together in the CZ's evolution and functioning. Specifically, these links include the following:

- The interrelationships between hydropedology and ecohydrology, and how they influence soil moisture, ground water recharge, ecological health and diversity, and environmental quality in general (e.g., Young et al., 2007; Li et al., 2009);
- The integration of hydropedology and hydrogeology, which can provide a more holistic view and prediction of subsurface flow and transport from the ground surface all the way down to the ground water (e.g., Lin, 2003);
- The linkage between hydropedology and hydrometeorology, which includes issues related to soil moisture and global climate change, soil carbon sequestration, greenhouse gas emission from soils, and remote sensing of soil climate (e.g., Lam et al., 2007);
- The coupling of hydropedology and biogeochemistry, including the identification of hot spots and hot moments of biogeochemical cycles in different ecosystems (e.g., McClain et al., 2003; Lohse et al., 2009);
- The study of palesols and palehydrology, which shows valuable historical records of past environment and ancient landscape-soil-water relationships (e.g., Ashley and Driese, 2000);
- The connection between hydropedology and land use planning, because how natural soils "throb" upon precipitation inputs under various climatic regimes offers clues as to "what" can best be done and "where" with the lowest risks and the greatest opportunities for land use and management (e.g., Bouma, 2006).

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4 Opportunities for Advancing Critical Zone Science and Hydropedology

Given the growing interests in CZ science (e.g., Brantley et al., 2007; Richter and Mobley, 2009) and hydropedology (e.g., Lin et al., 2006a, 2008a; Li et al., 2009), it is beneficial at this early stage of their developments to discuss some possible ways for their advancements. In this

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section, three approaches are discussed, which are based on recent efforts in Critical Zone Observatories (CZOs) and other similar efforts around the world (Richter and Mobley, 2009). Key approaches or steps that need to be taken or strengthened in order to achieve significant advancements in our understanding and prediction of the CZ are explored, with a focus on those germane to hydropedology. No attempt, however, is made here to exclusively consider all possible approaches and aspects. The examples present below are meant to be illustrative, rather than exhaustive. Hopefully, such a discussion would stimulate more coming from the community.

4.1 Integrated Systems Approach

Most natural systems are irreducible, meaning that the systems properties cannot be revealed by a reduction to some observations of the behavior of their components. Instead, it is necessary to observe the entire system to capture its behavior because everything is dependent on everything else by direct or indirect linkages. Tiezzi (2006) suggested the need for a new theory to describe ecosystem's behavior, because the laws that describe the system may be qualitatively different from those that govern its individual units. Reductionist's approach does not work well for understanding the complexity in soils and the CZ because of evolutionary nature and interactions and feedback loops among individual units in the system. Toffler (1984) remarked, "*One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components. We are good at it. So good, we often forget to put the pieces back together again …We say ceteris paribus–all other things being equal. In this way we can ignore the complex interactions between our problem and the rest of the universe.*"

The four general characteristics of the CZ discussed in Section 2.2 offers a holistic framework for a systems understanding of the CZ (Fig. 3). Lin (2010b) further discussed the use of non-equilibrium thermodynamics, general systems theory, and complexity science to embrace an evolutionary and holistic worldview of the soil and the CZ that goes beyond the classical mechanistic and reductionistic worldview. In particular, Lin (2010b) emphasized the accumulation of entropy and information, in addition to the conservation of energy and mass, in the evolution of the CZ. Entropy, as a core thermodynamic variable, offers a possible new perspective to understand the interactions between soil systems and their surrounding environment in the CZ. Entropy has the intrinsic properties of time irreversibility as well as

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We normally monitor pedons to collect point-based data and model landscapes attempting to understand areal-wide patterns. A key connecting these two is the mapping of various soils and landscape features, because the fabric of soils over the landscape provides valuable clues to appropriate selection of monitoring/sampling sites and the design of modeling experiments. Relatively static properties such as topography and soil texture may be mapped to assist in monitoring and modeling, while dynamic properties such as hydrology and soil moisture should be monitored to refine model predictions and to provide ground truthing for mapping and remote sensing. Mapping also provides a means of diagnosing and stratifying the landscape before designing experiments and selecting optimal number of monitoring sites. Thus, the value of mapping in the study of the CZ and hydropedology should not be overlooked. ¶
The 3M strategy has been employed in the hydropedology study in the Shale Hills Catchment, one of the first U.S. National Critical Zone Observatories (Lin et al., 2006; Lin, 2006; Lin and Zhou, 2008). Based on comprehensive surveys and various maps developed for this catchment, an extensive soil moisture monitoring network has been developed (Fig. 10). Example data shown in Fig. 10b demonstrates the importance of location, depth, and flow pathways in soil monitoring. Valuable experience from our initial hydropedology studies ... [79]

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quality and information that other thermodynamic functions lack (Tiezzi, 2006; Jørgensen et al., 2007; Ulanowicz, 2009). *"Conservation without evolution is death. Evolution without conservation is madness."* These words of Bateson (1979) underline a fundamental characteristic of complex natural systems such as soils and the CZ.

Integration of disciplinary research is a key to future progress in CZ science. Many other disciplines besides hydropedology are involved in the CZ (e.g., Brantley et al., 2006, 2007; Richter and Mobley, 2009; Li et al., 2009). Figures 1 to 5 have illustrated this point. In sum, the CZ's general characteristics shown in Fig. 3 imply the following four grand challenges for advancing CZ science that demands an integrated systems approach:

- *Forcing*: Traditional geosciences have viewed humans, life processes, and atmospheric forcing as external drivers rather than as intrinsic parts of the whole system. It is these forces that have driven the CZ far from equilibrium, and confronted the CZ with chances and choices in its evolution (Lin, 2010b). The hydrologic community is now keenly interested in human impacts, biological forcing, and climate change on the hydrologic cycle (CUAHSI, 2007); the geochemical community is tackling weathering systems science that includes climatic, tectonic, and anthropogenic forces (Anderson et al., 2004); and the soil science community is embracing human land use/management impacts on soils as a new frontier (Richter, 2007).
- *Coupling*: Biogeochemical and ecological cycles are tightly coupled with the hydrologic cycle and soil reservoir. Reconciliation of the geological "big" cycle and the biological "small" cycle is essential for understanding and predicting the CZ. The classical average budget-based cyclic approach needs to be complemented by more process-based dynamic coupling to quantify enormous variability across scales.
- *Interfacing*: The presence of interfaces between two or more layered compartments is an important element of the CZ. The role of these interfaces in understanding the interactions and feedbacks between compartments and their regulatory impacts on the whole CZ deserves more attention in defining research questions for the CZ (Vereeken, 2009). Key interfaces in the CZ provide fertile ground for transformative research, where interactions among physical, chemical, biological, and anthropogenic processes prevail, leading to "hot spots" and "hot moments" of the CZ's behavior (McClain et al., 2003).

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- *Scaling*: Scale bridging remains a big challenge in nearly all hydrologic, pedologic, biogeochemical, and ecological studies. It is highly desirable to clarify how dominant processes and their controls change with spatial and temporal scales, and to explore quantitative means to transfer knowledge from microscopic (e.g., molecular and pore), to mesoscopic (e.g., pedon and catena), macroscopic (e.g., watershed and regional), and to megascopic (e.g., continental and global) levels. The intermediate scale associated with medium number systems (Fig. 5) deserves particular attention, which is most challenging.

4.2 Evolutionary Mapping-Monitoring-Modeling Framework

An iterative loop of mapping, monitoring, and modeling (3M) can provide an integrated and evolutionary approach to address the complexity and dynamics in the CZ (Fig. 9), at least as a good starting point to deal with many uncertainties involved. Such an evolutionary approach allows the development of adaptive strategy and the refinement of models and monitoring networks as knowledge and database are accumulated.

Monitoring is essential to record temporal dynamics and coupled cycles in the CZ. It also provides model inputs, validates model outputs, and supplies ground truthing for remote sensing. Considering the multi-phase nature of the soil system (gaseous, liquid, solid, and biotic phases), it is inadequate to determine soil change by only one characteristic, because each soil phase and property has its own characteristic response time. Some soil changes are inherently long-term, undetectable in a short period of time, but irreversible and threshold-like in the long-term. This evolutionary process presents significant challenges to designing and implementing scientific monitoring program for the CZ. However, ecosystem services, biodiversity, sustainable land management, and global environmental changes all depend on the evolution of the soil. Therefore, long-term monitoring of soil changes is essential.

Models are necessary tools for quantitative assessment, knowledge integration, and prediction. Models can also guide the design and site selection for monitoring and ground truthing. When integrated with real-time monitoring and spatially-distributed mapping, models can effectively address temporal trends and spatial patterns. However, the hydrology community is awaiting a conceptual breakthrough that goes beyond the classical small-scale physics (Beven, 2006; Kirchner, 2006; McDonnell et al., 2007; Lin, 2010a). Subsurface flow networks are often

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Quantifying soil heterogeneity in the field at high spatial and temporal resolutions demands technological advancements. While landforms and vegetation can now been mapped with high resolution (e.g., using Light Detection and Ranging or LiDAR for DEM, and the earth observation satellite IKONOS for land use/land cover), there is a "bottleneck" for *in situ* high-resolution (e.g., submeter to centimeter) and spatially-temporally continuous and non-invasive mapping of subsurface architecture. This "bottleneck" has constrained our predictive capacity of many soil and hydrologic functions in the subsurface. Thus, there is a great need to develop enhanced tools and techniques for precision and noninvasive mapping/imaging of the subsurface *in situ*, so that subsurface processes can be better understood and predicted.¶
We also need new ways of mapping soils beyond the classical approaches where soil taxonomic units, rather than soil functional units, are used in mapping. The concept of *Hydropedologic Functional Unit (HFU)* could be defined as a soil-landscape unit having similar pedologic and hydrologic functions to provide a means of cartographically representing important landscape-soil-hydrology functions (Lin et al., 2009). The goal of such HFUs is to subdivide the landscape into similarly functioning hydropedologic units by groupin ... [80]

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embedded in land mosaics, which may be conceptualized to provide an alternative to modeling coupled hydrologic and biogeochemical processes, where internal network structures govern vertical and lateral preferential flow dynamics and threshold-like hydrologic response (e.g., Tromp Van Meerveld and McDonnell, 2006; Lehmann et al., 2007; Lin et al., 2008b). Such an approach, however, hinges on technological breakthrough in characterizing subsurface networks.

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The value of mapping in the study of the CZ should not be overlooked. Monitoring generally collects point-based data, while modeling often attempts to cover large areas. A key to connect the two is the fabric of the subsurface over the landscape that should be mapped at appropriate spatial and temporal resolution, so that meaningful extrapolation and upscaling of point-based data could be made. Mapping also provides a means of diagnosing and stratifying the landscape for determining optimal location and number of monitoring sites as well as designing meaningful model experiments. Mapping is also a prerequisite for spatially-distributed modeling. While geostatistics provides powerful interpolative tools after an extensive dataset has been gathered on a particular area, it is not a powerful extrapolative tool. Geostatistical functions should be derived from landscape stratified units (such as soil type, geology, land use) and not indiscriminately across a broad landscape without prior partitioning of the causes of variability.

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Inherent heterogeneity of spatial structures across scales remains a major challenge in understanding the CZ. All processes within the subsurface are bound to this structural framework, which is typically unknown or hard to quantify with currently available technologies (Vogel and Roth, 2003). This is a fundamental difference compared to atmospheric monitoring where the heterogeneity of the system can be explored at one sensor location. But the signals of two sensors at nearby locations in many soils may be completely uncorrelated. This is why we need the mapping of the subsurface heterogeneity. Then, and only then, can the point-based monitoring provide the required observations to develop and improve predictive potential of process-based models (Vogel, 2009). The terrestrial land is unlike atmosphere and ocean (which can be modeled as a continuous fluid); rather, the land poses hierarchical heterogeneities with controlling structures different at various scales, which dictate flow and reaction pathways and patterns. For example, flow direction and its temporal changes is as important as flow rate in three-dimensional hydrologic and biogeochemical processes in the heterogeneous landscape.

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Significant breakthroughs in technologies are also needed to advance CZ science and hydropedology, such as:

- New and improved sensors that are reliable in all seasons and robust for long-term monitoring. Many existing sensors may break in the field within a few months or do not work at all in frozen conditions. Besides, many CZ properties still can not be monitored *in situ* with a real-time sensor;
- Subsurface characterization technologies including geophysical tools and remote sensing that can provide continuous map or image the subsurface architecture and processes *in situ* and noninvasively. Currently, the spatial resolution, or temporal frequency, or depth penetration of many of these technologies are limited for belowground investigations;
- Online databases that are opened to the community and are comprehensive, together with necessary visualization and analysis toolboxes for using the databases effectively.

4.3 Fostering a Global Alliance

With growing interest in international scientific communities to establish various environmental observatory networks and to address "big" science questions, a synergistic effort to foster a global alliance for monitoring, mapping, and modeling of the CZ is desirable. Long-term monitoring, along with precision spatial mapping and process-oriented modeling, of the CZ across scales and geographic regions (Fig. 9) can serve many purposes of societal importance. Optimization of whole systems for multiple benefits rather than one benefit permit synergistic outcomes and would be more cost-effective in the long-run. An integrated network for observing, modeling, and sustaining the Earth's CZ *as a whole* is in its early stages of development, but it is clear that it will require inputs from many basic and applied disciplines. No one team or organization can do that alone, and a diversity of funding sources supporting a heterogeneous mixture of overlapping programs is probably the best formula for long-term stability of observatory networks (Keeling, 2008). Therefore, a global alliance is suggested here.

In 2007, the U.S. National Science Foundation funded three Critical Zone Observatories (CZOs) (Fig. 9) "*that will operate at the watershed scale and that will significantly advance our understanding of the integration and coupling of Earth surface processes as mediated by the presence and flux of fresh water*" (http://www.nsf.gov/pubs/2006/nsf06588/nsf06588.pdf). In

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It is important to connect mapping with long-term monitoring of the CZ. A major challenge in understanding the CZ is the inherent heterogeneity of three-dimensional spatial structures across scales. All processes within the subsurface are bound to this structural framework, which is typically un ... [81]

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2009, additional three CZOs have been funded (Fig. 9). In the meantime, German's Helmholtz Association has established four TERestrial ENvironmental Observatories (TERENO) in 2008-09 to investigate the consequences of global change for terrestrial ecosystems and the associated socioeconomic implications (http://www.tereno.net/). In 2009, the EU 7th Framework Programme has selected to fund a project that supports four CZOs in EU (http://cordis.europa.eu/fp7/). Similar efforts are being pursued in other countries such as Australia and China. Therefore, now is the right time to foster a global alliance for studying the CZ, which may best be realized in a coordinated way to maximize the benefit for global environmental research. In addition, interests have also emerged in the community to forge independently conceived observatories into a network from which broader understanding—larger spatial scales, cross-site comparisons, and deeper insights—may be gained (Anderson et al., 2008). Together, our capability to predict the behavior and evolution of the CZ in response to changing environment can be improved significantly, if such a global alliance can be effectively fostered.

Besides spatial networking of CZOs and alike, long-term monitoring also is critical. In this time of accelerating global change, continuous CZ observations are essential as they have the potential to open our eyes for unexpected but relevant developments and processes. For example, the famous "Keeling Curve" of long-term CO_2 data demonstrated the value of continuous recording of a seemingly *routine* atmospheric measurement, which turned out to be a vital sign of the Earth's climate and led to the first alert to the world about the anthropogenic contribution to the "greenhouse effect" and global warming (Keeling, 2008). Similarly, the long-term study at the Hubbard Brook Experimental Forest demonstrated undiminishing scientific returns of *routine* measurements that led to the discovery of "acid rain" in North America (Likens et al., 1972. Likens and Bormann, 1974). Long-term recording of the health of the CZ's foundation—soil, through monitoring its "blood pressure" (soil water potential), temperature, respiration, carbon sequestration, and other potential key signs of global land change, is essential to the sustainability of ecosystem services, continued productivity of the soil, quality of water and air, and a balanced growth of human society with natural systems.

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To proceed with such a global alliance, we should develop international monitoring protocols and standards. Once the agreed protocols and standards are developed, then the selection of sites for major soils of the world along heterogeneity gradients would be an important next step. Mapping and modeling should be used in assisting the selection of major monitoring sites. Once monitoring sites are chosen, real-time monitoring datasets should be continuously utilized, in combination with precision mapping and process-based modeling, to provide spatial extrapolations and temporal inferences about the trends and feedbacks in the CZ.¶

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5 Summary and Conclusion

The emerging interests in the Critical Zone and the establishment of Critical Zone Observatories (and alike) in different parts of the world provide an excellent opportunity to advance the understanding and management of the most complex and heterogeneous biomaterials on the Earth surface. Key approaches or steps discussed in this paper to achieve significant advancements include (but not limited to):

- Iintegrated systems approach that cross-fertilizes the principles of energy and mass conservation and entropy and information accumulation in interdisciplinary and multiscale studies;
- Evolutionary mapping-monitoring-modeling framework that allows the development of both adaptive strategy and a systematic characterization of subsurface heterogeneity;
- Formation of a global alliance that monitors, maps, and models the CZ in a coordinated manner that can stimulate cross-site scientific comparisons, evolutionary treatment of organized complex systems, and deeper insights into the CZ.

Water and soil combined is a key to understanding the Earth's Critical Zone. While the soil is at the central junction of all the interacting compartments in the CZ, the whole CZ is much broader than soils and includes aboveground vegetation and belowground aquifer. A broadened perspective on soils is needed to propel soil science forward and to promote its integration with other bio- and geosciences using the unifying theme of the CZ.

Hydropedology is illustrated in this paper as an important (but not the only) contributor to the CZ study, which addresses the interface between the pedosphere and the hydrosphere. Hydropedology is concerned with how the subsurface heterogeneity develops and evolves, how soil architecture impacts flow and transport in the field, how soil distribution pattern influences hillslope and watershed hydrology, and how the hydrologic cycle feedbacks to pedogenesis and impacts soil functions. The fundamental questions of hydropedology call for quantitative connection between complex soil architecture and soil hydrologic functions and the improved understanding of how hydrology impacts soil formation and evolution. The hydrologic cycle (especially with global climate change), together with human activities (mainly through land use

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The crucial juncture of all the interacting spheres on the Earth surface is the product of five soil-forming factors plus human impacts. The pedosphere is a unique, relatively immobile, and highly heterogeneous and dynamic sphere. In contrast to the other spheres of the Earth system, the pedosphere can neither quickly intermix (as the atmosphere does), nor rapidly move laterally along the landscape (as water does), nor clearly be separated into individual units ... [85]

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and land management), have become prominent forces of changes in soils and the CZ, and thus deserve elevated attention in the integrated studies of the CZ.

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List of Figures

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Figure 1. Concepts of the Critical Zone, regolith, weathering profile, soil profile, and solum (modified from Schaetzl and Anderson, 2005). The unmodified/unweathered portion of the C horizon is labelled as D horizon (after Tandarich et al., 1994). All materials above fresh, unweathered bedrock (R horizon) are called regolith, which is equivalent to a broad definition of the soil. The Critical Zone is the broadest concept, going from the top of the tree to the bottom of the aquifer. Also illustrated here are (1) the abundance of microbes and insects in the soil, especially in the surface, and (2) fresh water seeping out of an aquifer and running over exposed bedrock.

Figure 2. The “7 + 1” roles of the soil from the Earth’s Critical Zone to Mars exploration: (1) Soil is a natural recorder of the Earth’s history through its formation and evolution under the influence of climate, organisms, parent material, relief, time, and human impacts; (2) Soil is a fresh water storage and transmitting mantle in the Earth’s CZ; (3) Soil is a gas and energy regulating geoderma in the land-atmosphere interface; (4) Soil is the foundation of diverse ecosystems; (5) Soil is a living porous substrate essential for plant growth, animal production, and food supply; (6) Soil is a popular material for a variety of engineering and construction applications; (7) Soil is a great natural remediation and buffering medium in the environment; and (8) Soil is a possible habitat for extraterrestrial life, if any can be found, and serves as a frontier in extraterrestrial explorations to explore signs of liquid water and life. In the lower panel, two models for the outlook of soil science are illustrated: one is a broad perspective (“outward” growth) and the other is a narrow view (“inward” contraction).

Figure 3. Schematic of the Critical Zone (CZ) open to continuous energy and mass exchange with the surrounding environment, where the conservation of energy (E) and mass (M) and the

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accumulation of entropy (*S*) and information (*I*) are at work simultaneously that dictate the evolutionary outcome and the functioning of the CZ. Irreversible evolution, coupled cycling, interactive layers, and hierarchical heterogeneity are characteristic of the CZ. The reconciliation of coupled geological and biological cycles vastly different in space and time are essential to the understanding of the complexity and dynamics of the CZ.

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Figure 4. Principle sub-cycles within the geological "big" cycle and the biological "small" cycle, which are integrated into the evolutionary hostory of the Earth and life.

Figure 5. ***Left***: A hierarchical framework for bridging multiple scales from the molecular to the global levels. Pedon at a local point is considered here as the basic scale (*i*) of observation or monitoring, and *i*±1…4 indicate arbitrary labels of larger or smaller scales. Note the gap exists in between scales. ***Right***: Three types of systems with respect to different methods of thinking. There is a wide gap between the two extremes, where systems in medium numbers are too complex for analysis and too organized for statistics (modified from Weinberg, 1975).

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Figure 6. Illustration of strong connection between ubiquitous heterogeneity and diverse preferential flow in natural soils. Two contrasting soil columns visualized under X-ray show earthworm borrows and root channels in an agricultural soil derived from limestone (left) and large amount of rock fragments in a forest soil derived from shale (right).

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Figure 7. A general sequence of soil development from a young Entisol (left) to a highly-weathered Ultisol (right) under well-drained conditions. The graduate formation of various soil horizons and the deepening of soil profile through time depend on the weathering rate of the underlying bedrock (R horizon), the accumulation rate of organic matter (O and A horizons), and the percolation rate of water through the soil profile. To reach a highly developed soil (such as an Alfisol and Ultisol), sufficient amount of water must not only enter the profile and participate in

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weathering reactions, but also percolate through the profile and translocate weathering products (such as solutes and clays). Further development from Alfisol to Ultisol leads to distinct eluviation of clay, iron, and aluminium oxides, leaving behind a light color and coarse texture E horizon and forming a high clay accumulation Bt horizon that often becomes an aquitard.

Figure 8. ***Upper:*** A common soil catena along an eroding hillslope in Australia, showing iron transformations and the formation of ferricrete in relation to iron mobilization and water flow pathways. ***Lower:*** Free-water levels at the end of a wet season (from March to June) along a toposequence near Torrens Creek, Queensland, Australia. The Yellow and Grey Kandosols (highly-weathered soils) are saturated, with shallow depth to free water (0-2 m), whereas the downslope deep Red Kandosols have much greater depth to free water (4-11+m). In both cases, different colors, mottle patterns, and ironstone contents of the soils are consistent with their distinctive soil hydrological regimes (from Coventry, 1982) (after McKenzie et al., 2004).

Figure 9. Iterative loop of mapping, monitoring, and modeling as an integrated and evolutionary approach to address the complexity and dynamics of the Critical Zone across scales and geographic regions. Shaded relief map at the top shows the locations of the Critical Zone Observatories (CZOs) funded in the U.S. (red stars indicate the CZOs funded in 2007, and white stars indicate the CZOs funded in 2009).

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Fig. 1

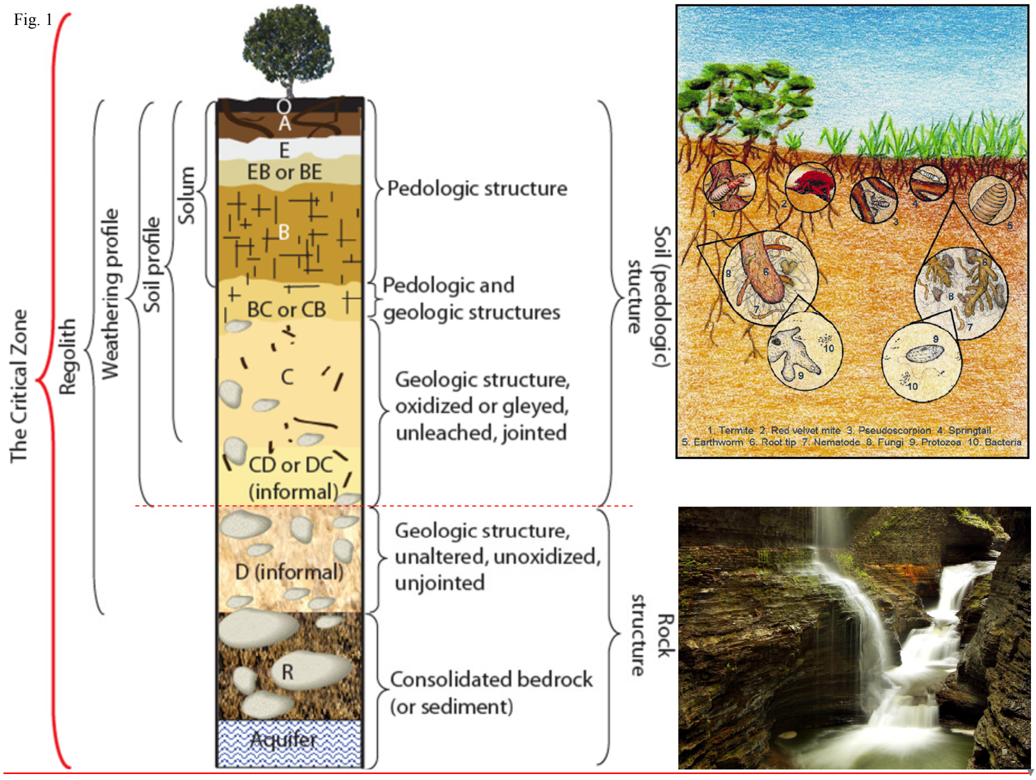

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Fig. 2

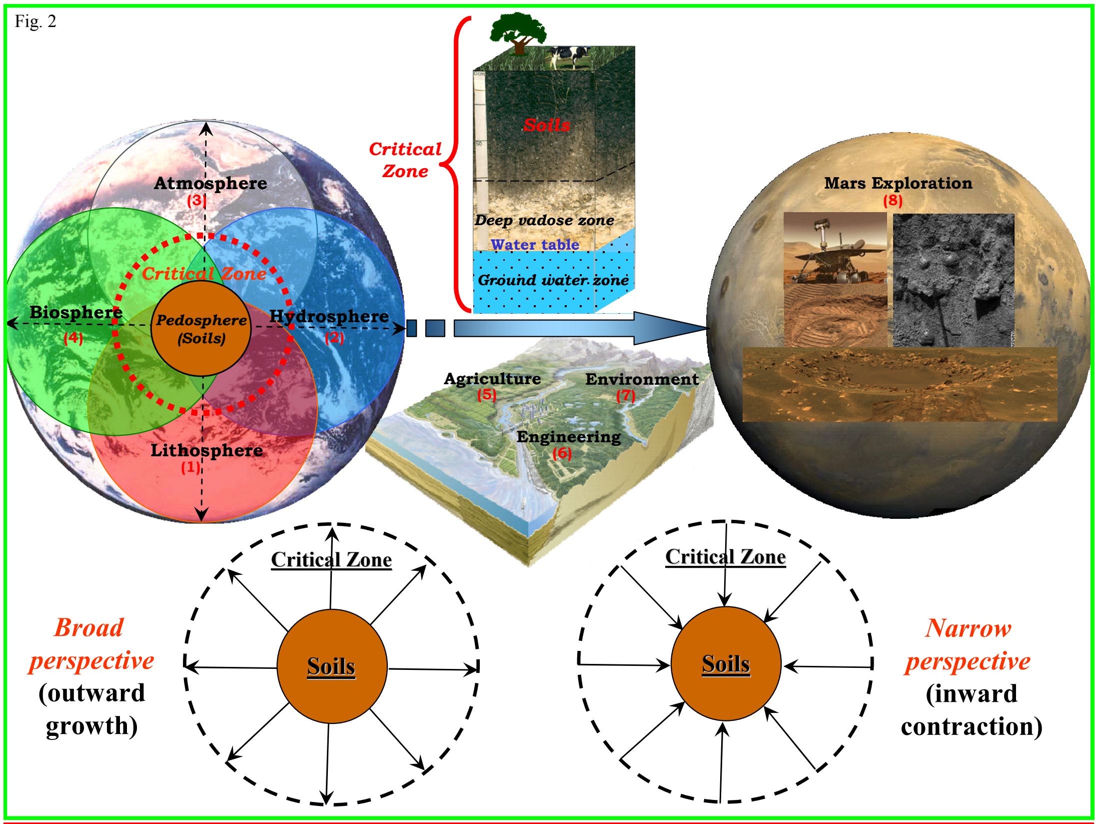

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Fig. 3

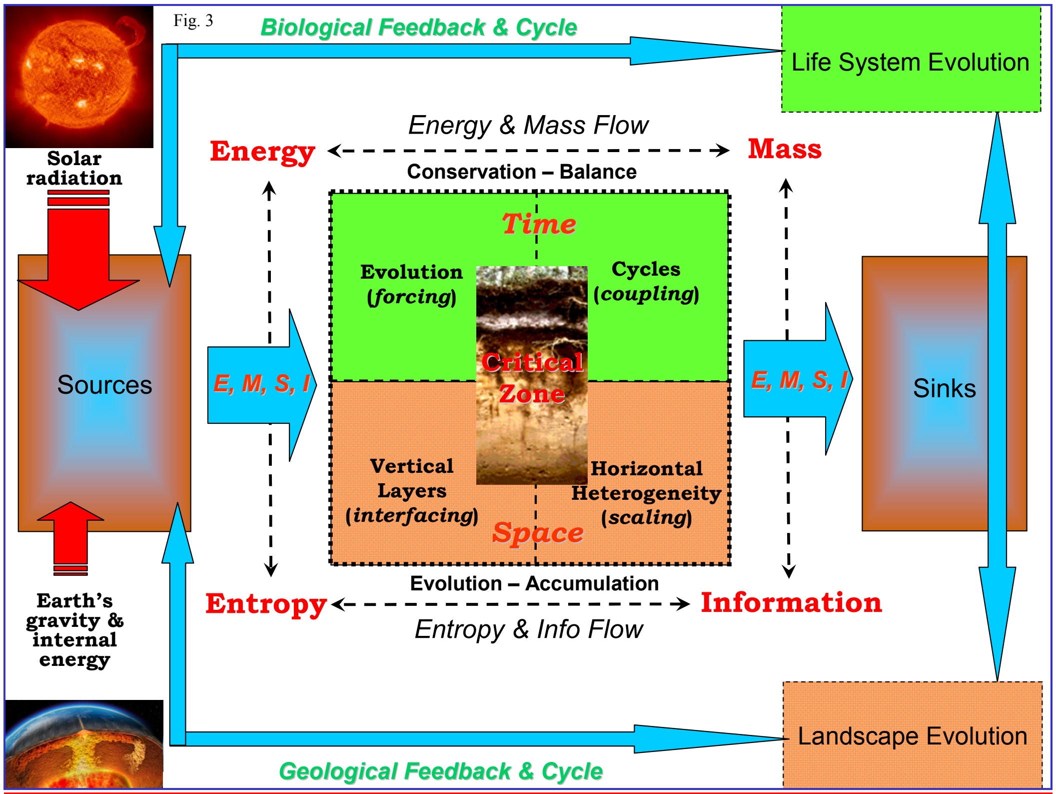

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Fig. 4

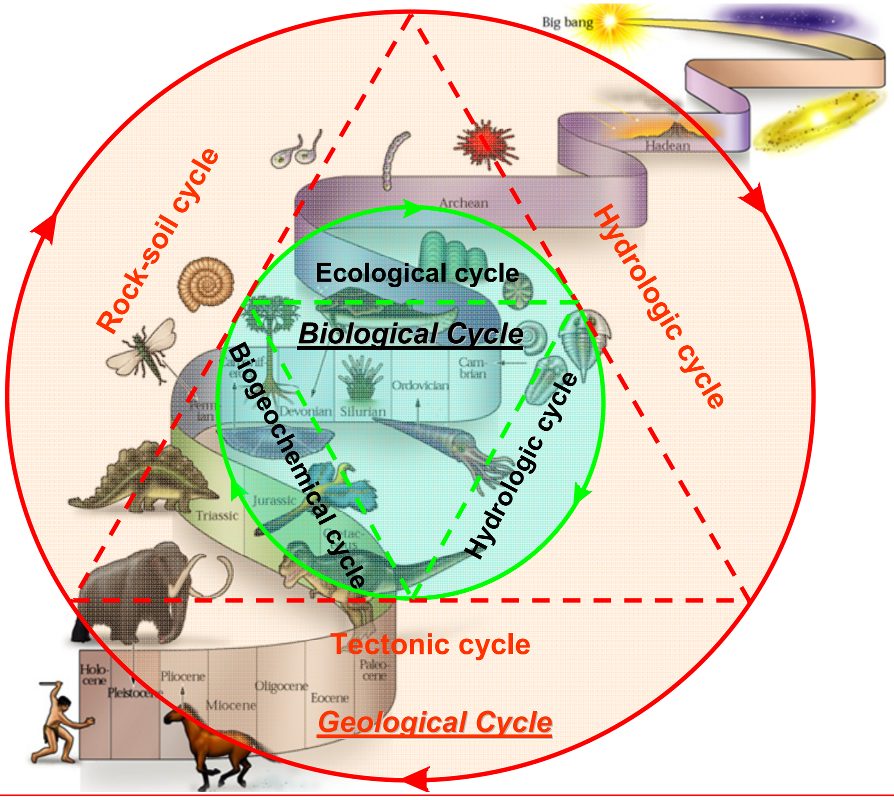

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Fig. 5

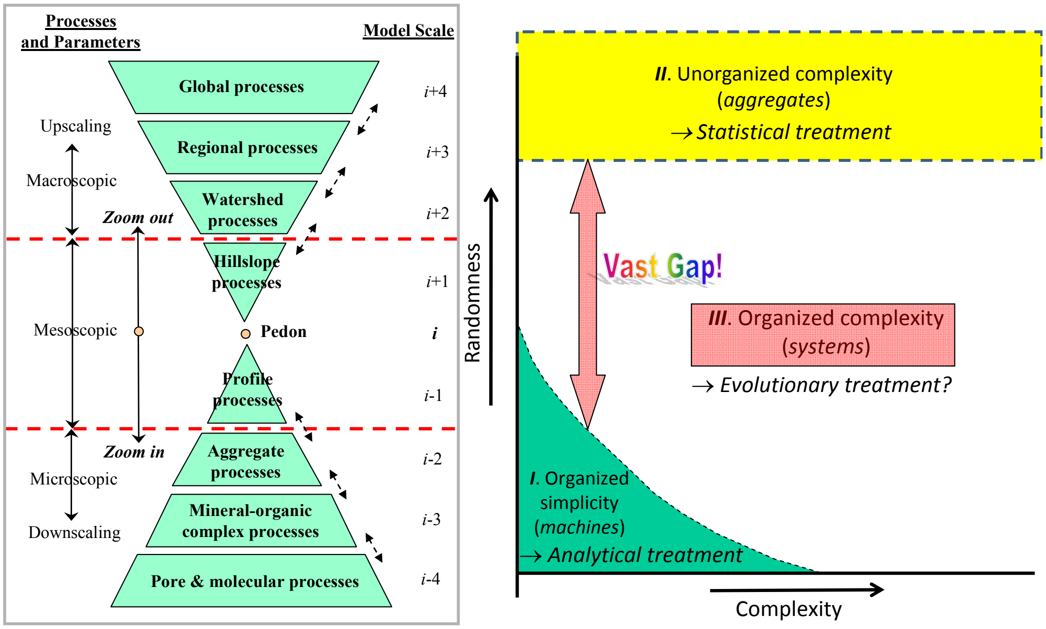

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Fig. 6

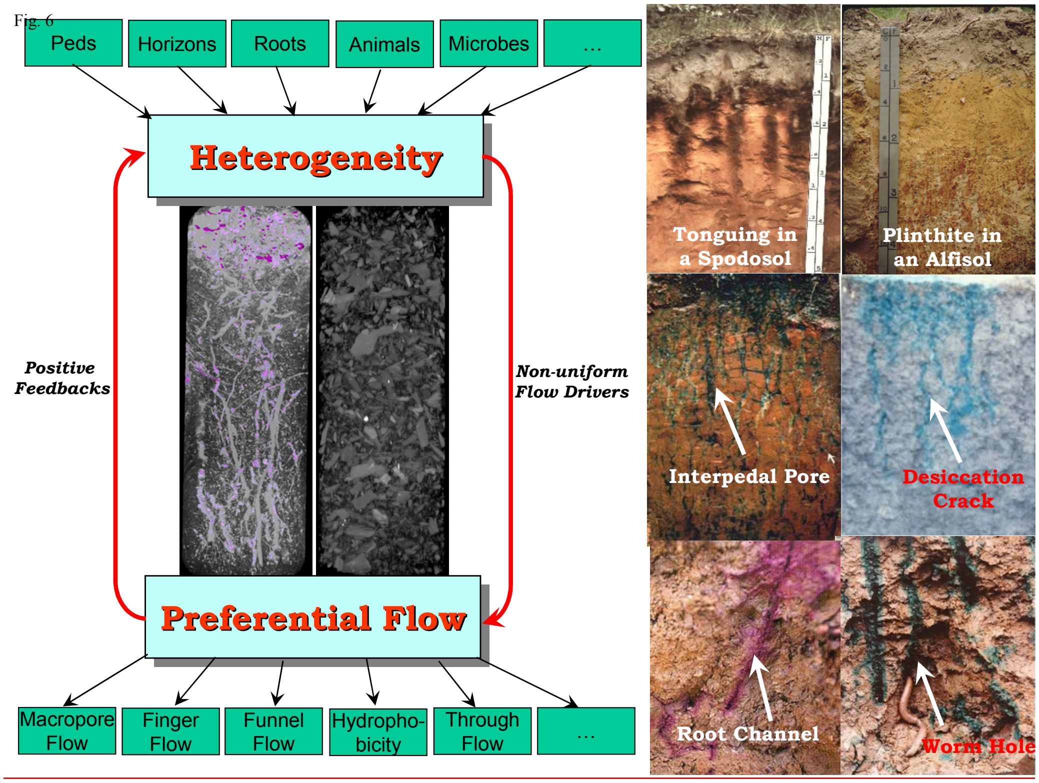

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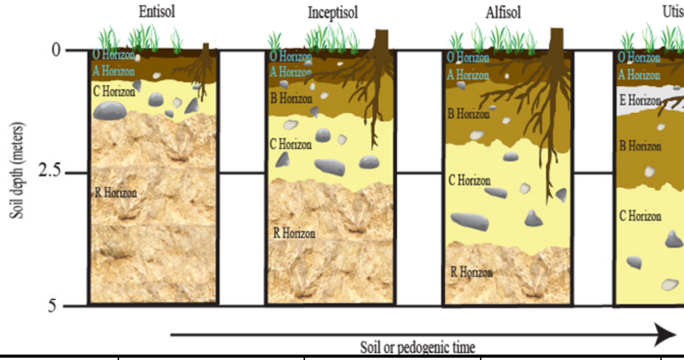
Fig. 7



Soil order	***Entisol***	***Inceptisol***	***Alfisol***	***Ultisol***
Pedogenic age (year)	10^0 — 10^2	10^2 — 10^4	10^3 — 10^5	10^4 — >10^6
Soil profile diagnostic feature	No B hor.	Weekly developed B hor.	Clay-enriched B, with base saturation > 35%	Kaolin and oxide-dominated B, with base saturation < 35%
Hydrologic feature	Water-restricting within <0.5 m	Moderate water storage and percolation	High water storage, deep percolation	B horizon hydraulic conductivity reduced, turning into an aquitard
Soil thickness (m)	0.01 — 0.5	0.1 — 2	1 — 5	5 — >10
Ksat in surface soil	Low	Moderate	High	High
Ksat in subsoil	Low	Moderate	High	Low
Preferential flow	Vertical & lateral	Mostly vertical	Mostly vertical	Vertical & lateral

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Fig. 8

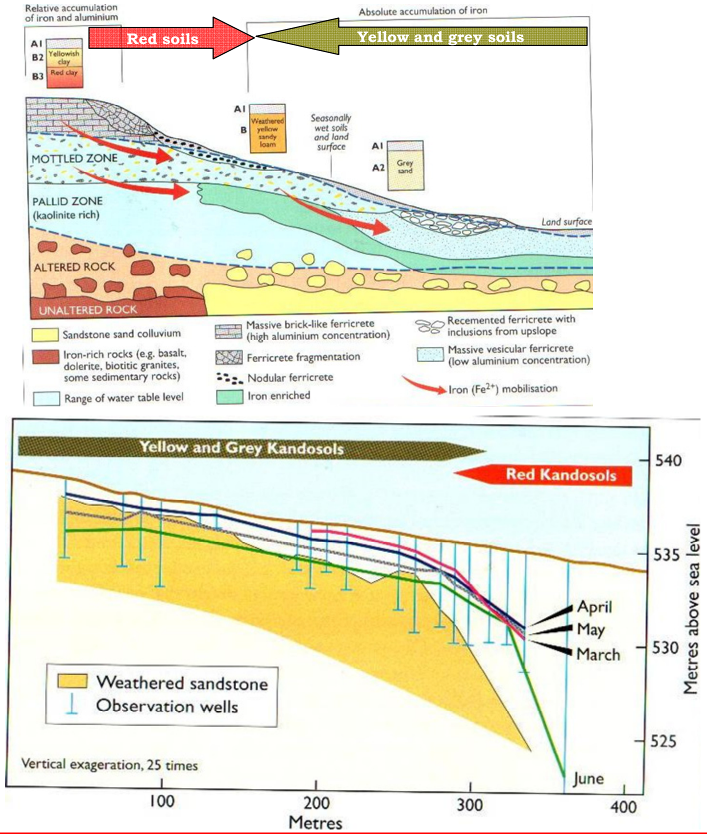

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Fig 1

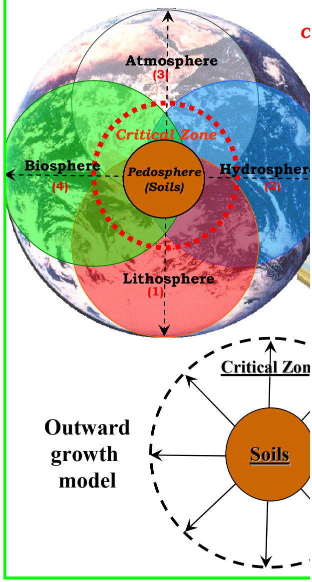

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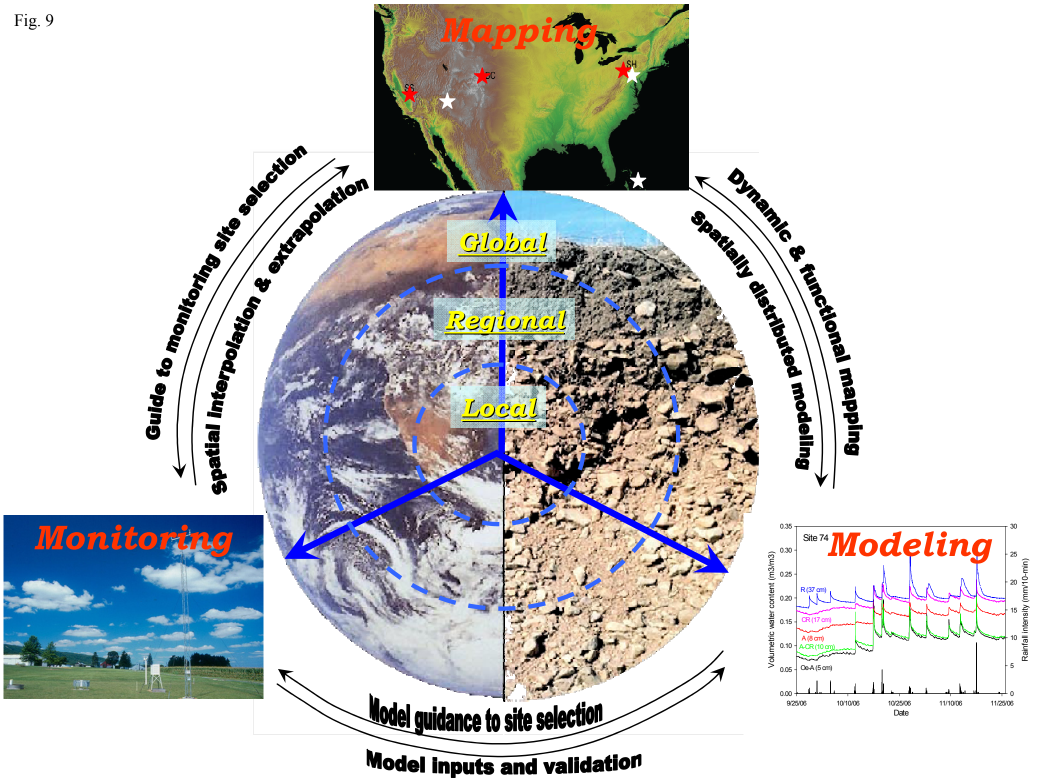
Fig. 9



Deleted: **Figure 1**. An inclusive vision for future soil science: 7 + 1 roles of the soil from the Earth's Critical Zone (CZ) to Mars exploration. The numbered roles of soils are: (1) Soil is an Earth history recorder as soil is a natural body formed under the influence of climate, organisms, parent material, relief, and time (i.e., the five soil-forming factors) in the Earth's system; (2) Soil is a fresh water storage and transmitting mantle in the Earth's CZ; (3) Soil is a gas and energy regulating geoderma in the land-atmosphere interface; (4) Soil is the foundation of diverse ecosystems; (5) Soil is a living porous substrate essential for plant growth, animal production, and food supply; (6) Soil is a popular material for a variety of engineering and construction applications; (7) Soil is a great natural remediation and buffering medium in the environment; and (8) Soil is a frontier in extraterrestrial explorations to explore signs of liquid water and life. This diagram also depicts the cyclical, vertical, and horizontal heterogeneity involved in the CZ. In the lower portion of the graph, two models for future soil science are illustrated: an "outward" growth vs. an "inward" contraction. The outward growth model suggests a broadened perspective of the soil and its synergistic integration with other disciplines within the framework of the CZ. The inward contraction model, on the other hand, implies a classical and narrow view of the soil and a confined perspective of the CZ (by equating the CZ to the soil alone).¶ ... [89]

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