The Role of Data and Inference in the Development and Application of Ecological Site Concepts and State-and-Transition Models

By Jason W. Karl and Curtis J. Talbot

On the Ground

- Information embodied in ecological site descriptions and their state-and-transition models is crucial to effective land management, and as such is needed now.
- There is not time (or money) to employ a traditional research-based approach (i.e., inductive/deductive, hypothesis driven inference) to address the unknowns in developing and documenting ecological site concepts.
- We propose that the development of ecological site products is a dynamic task of defining concepts and processes that best explain the available data (i.e., abductive reasoning), and as such a more iterative approach to their development is needed than is currently used.
- Under the proposed approach, ecological site concepts are never viewed as final but only the best representation that is supported by available knowledge and data.
- The natural result of this way of thinking is that products like ecological site descriptions and state-and-transition models should continually be tested and improved as new data become available.

Keywords: ecological site, state-and-transition model, inference, scientific method, rangeland management, monitoring.

Rangelands 38(6):322–328
doi: 10.1016/j.rala.2016.10.009

"H*ow many licks does it take to get to the center of a Tootsie Roll Pop? The world may never know."* – Tootsie Roll Pop commercial beginning in 1969.

A long-running TV commercial for Tootsie Roll Pops that aired in the United States beginning in 1969 depicted the cartoon story of a boy, Tootsie Roll Pop in hand, asking the wise owl the following question: "Mr. Owl, how many licks does it take to get to the Tootsie Roll center of a Tootsie Pop?"[i] The owl takes the sucker from the boy and replies, "Let's find out." After three licks of the sucker, the owl crunches to the center, and responds, "Three!"

An often-asked question regarding development of ecological sites is, "How many data points or plot locations are needed to develop and validate an ecological site concept?" We contend that this question is akin to asking how many licks it takes to get to the center of a Tootsie Roll Pop, and that the answer could range from a very small or very large number depending on the approach and philosophy of the "Wise Old Owl" (ecologist/soil scientist) you ask. Furthermore, we suggest that this is the wrong question entirely because it is predicated on the erroneous ideas that an ecological site concept is static, that a final/conclusive ecological site description (ESD) can be achieved, and that an ecological site concept or its supporting documentation is not useful (or trustworthy) until that final ESD is finished. Rather, we propose that an iterative, dynamic approach to developing data-supported ecological sites and ESDs is needed.

To respond effectively and quickly to resource management concerns, rangeland professionals need information on land potential and expected responses to disturbances or treatment. For this reason, ecological sites are one of the most useful concepts for supporting land management activities.[1] An ESD and its state-and-transition model (STM) describes in concise terms the potential plant communities a site could support (e.g., states and phases) and the processes (e.g., succession, disturbances, management activities) that cause transitions between states.

[i] See the commercial at https://en.wikipedia.org/wiki/Tootsie_Pop#Commercials.

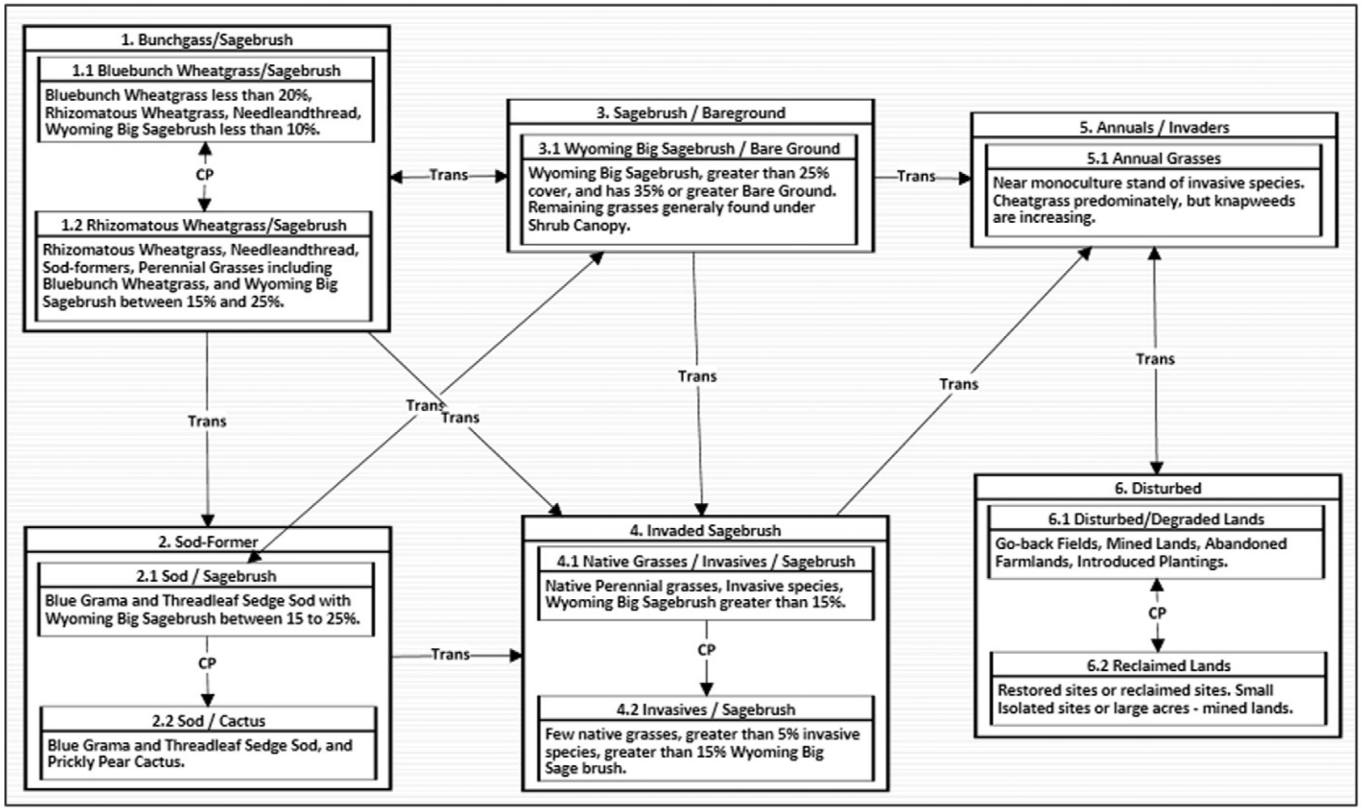

Diagram Legend

T 1-2	Frequent Grazing (year-long), Brush management, Fire or Drought.
T 1-3	Frequent and severe Grazing, No Fire, Drought
T 1-4	Frequent and severe Grazing, Fire, Drought
T 2.1-3	Frequent or severe grazing, Drought
T 2-4	Fire (wild or prescribed), Brush Management, Drought, Frequent or severe Grazing, Disturbance with seed source
T 3-4	Drought, Fire (wild or prescribed), Frequent or severe grazing, Brush Management or a disturbance with seed source.
T 3-5	Fire (wild or prescribed), Frequent or severe grazing, brush management, Disturbance with seed source.
T 4-5	Fire (wild or prescribed), Frequent or severe grazing with drought or insect damage/brush management
T 6-5	No Use, Fire (wild or prescribed), Frequent or severe Grazing, Drought
R 3-1	Prescribed Grazing and Brush Management
R 3-2.1	Long Term Prescribed Grazing, Brush Management
R 5-6	Intensive Pest/weed management, re-seeding the site ? Success is low and highly variable.
CP 1.1-1.2	Drought, Moderate Continuous Season Long Grazing.
CP 1.2-1.1	Prescribed Grazing, and Long Term Perscribed Grazing, Fire (prescribed or wild), brush management.
CP 2.1-2.2	Frequent or severe grazing, Drought, Intensive Brush Management, Fire.
CP 4.1-4.2	Frequent or severe grazing, wildfire, drought, continued disturbance.
CP 6.1-6.2	Seeding, Brush Management, Weed conrol.
CP 6.2-6.1	No use, No Fire, Long Term Prescribed grazing, Frequent Severe Drought.

Figure 1. Example STM from the Loamy 5-9 Big Horn Basin Precipitation Zone ecological site (R032XA122WY) in Wyoming.

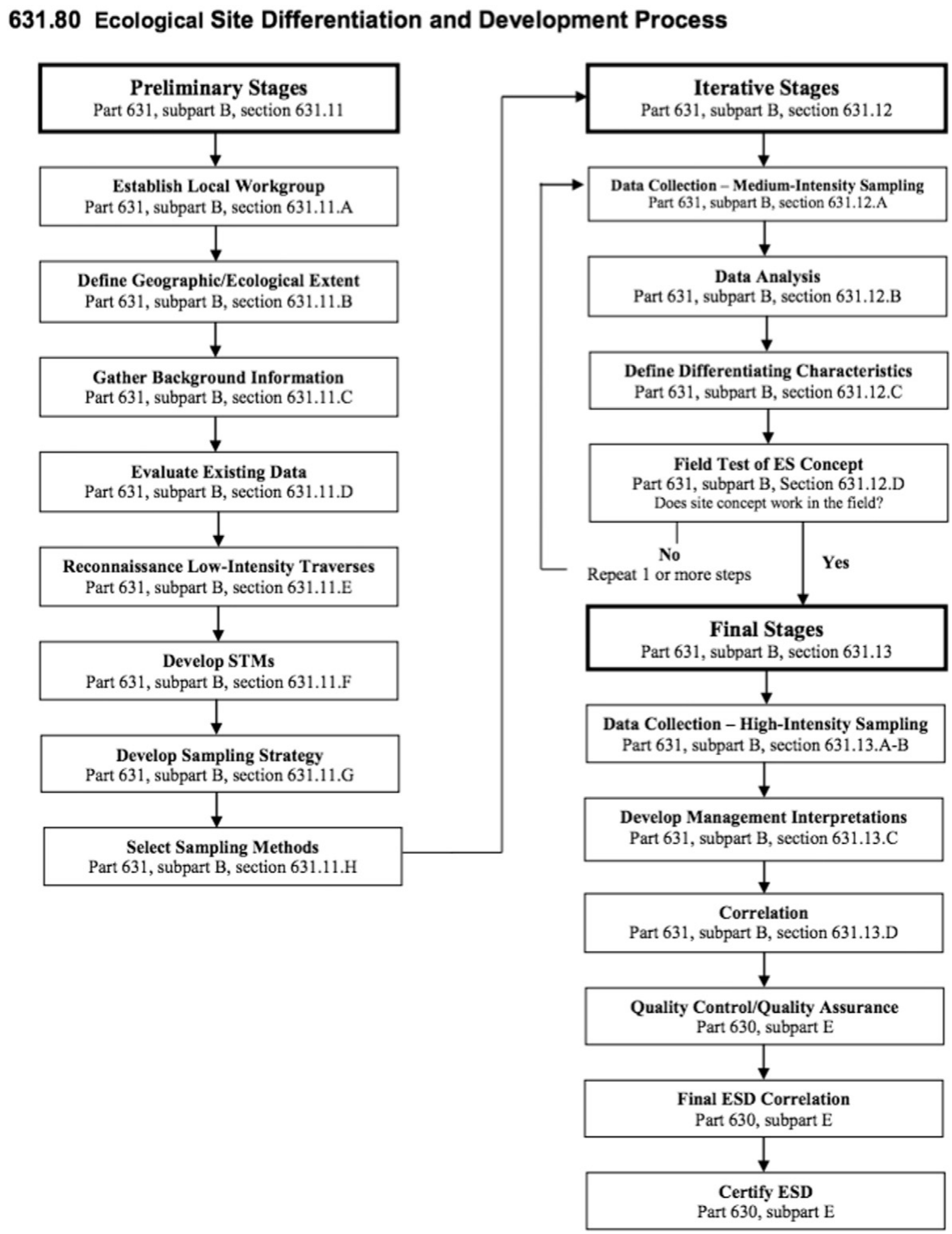

Figure 2. The current ecological site development process from the National Ecological Site Handbook[6] has as its conclusion a final, certified ecological site description (ESD) and state-and-transition model (STM) that is the result of multiple (and sometimes iterative) data collection and testing steps. The high bar of completeness of an ESD and its STM may contribute to long delays in ESDs being completed and made available to rangeland professionals.

For example, an ecological site STM and its accompanying documentation should be able to address the following types of questions (Fig. 1): Does an ecological site have the potential to produce adequate sagebrush (*Artemisia* spp.) for greater sage-grouse (*Centrocercus urophasianus*) habitat, and if so, what states can provide suitable habitat? What is the expected range of forage production for an ecological site that is (or is not) in its reference state? What is the potential effect of frequent burning within an ecological site?

Additionally, the information in an ecological site's STM is useful for identifying what aspects of an ecosystem to monitor (i.e., indicators) and how to interpret their changes over time.[2,3] These so-called functional indicators of land health help target management and monitoring toward measurable ecosystem properties that relate to key management goals. For example, an STM may indicate that excessive grazing pressure causes increases in bare ground and loss of perennial herbaceous species that may contribute to a transition from a reference state to a depleted shrub state. In this case, two important indicators are amount of bare ground and abundance or cover of herbaceous species.

An ecological site STM, as a type of conceptual model, should ideally be a complete description of the components, composition, and functioning of a type of land to the best of our knowledge.[4,5] The information to create an ecological site STM comes from diverse sources such as scientific research, local and expert knowledge, and empirical observations.[6,7] However, a diversity of conditions and processes exists within an ecological site and while the ecological site concept is based around some average value, the majority of the landscape will differ by degrees from this central concept. An additional, and equally important, role of the ESD and STM is to describe the variability present within an ecological site. An important additional function of an ecological site STM is to highlight knowledge gaps in ecosystem structure or function to guide additional research efforts.[2]

Data (e.g., empirical observations of natural systems) play a key role in developing and validating ecological site STMs (Fig. 2). Within the existing ecological site development process, data are used in creating and testing the site concepts, defining the differentiating characteristics of the site, and developing the management interpretations. The role of existing data in the current process, though, is largely limited to developing the initial concepts and to ad hoc validations of aspects of the site or its STM.

We argue, however, that the current ecological site development process is over burdened with data requirements and expectations of completeness before STM products can be released for use. Our objectives in this paper are to examine the role of data and inference in developing ecological site concepts and their STMs and to propose an alternative approach for developing STMs that will ultimately produce better and more useful models in a timelier and cost-effective manner.

The Ecological Site Development Process Inductive/Deductive Reasoning

Development of ecological site concepts and the models that describe their states and transitions is a process of synthesizing available research with expert and local knowledge. The current workflow for developing an ecological site and defining its attributes (Fig. 2) follows an inductive/deductive process of reasoning and inquiry.

Inductive reasoning entails making generalizations from a set of specific observations with the goal of induction being to discern patterns from data.[8] This type of reasoning can be very helpful in the early, "creative" phases of research to develop hypotheses or to posit mechanisms for how a system functions. The Preliminary Stages of the ES development process (Fig. 2, left-side), where existing data and knowledge are synthesized into preliminary ecological site concepts and STMs, are typically inductive steps. One limitation to inductive reasoning, however, is that it can be limited in situations where existing data or knowledge are incomplete or inconclusive. For this reason, the ES development process typically encourages collection of new data (i.e., low-intensity traverses) over a wide range of conditions from which the inductive phase of creating ecological site concepts can occur.

Deductive inference starts with defining general rules or theories, which are tested by observation or experimentation (e.g., hypothesis testing). The deductive phase of ecological site development (Fig. 2, right-side) consists of validating and refining ecological site concepts and STMs by making predictions of the expected attributes and patterns of an ecological site and testing those predictions with data collected specifically for that purpose. This same process may also be used to develop and test hypotheses to address knowledge gaps in STMs (e.g., unknown transition drivers).

An inductive/deductive approach is effective at synthesizing hypotheses from existing knowledge, highlighting and addressing knowledge gaps, and proceeding to a final product. This classic approach to developing ES concepts and STMs can become challenged, however, in highly dynamic systems in which clear ES concepts are difficult to define (e.g., riparian systems), in situations in which little is known about a land type, or when ES concepts need to be defined at coarser scales. An inductive/deductive model for developing and validating ES concepts is a data hungry process that often progresses slowly toward its goal of a well-defined and validated end product. Knowledge gaps and validation of ecological site attributes are treated as research hypotheses to be tested with custom data sets. Regardless of how much research has been done, though, there will never be enough data to satisfy all the knowledge gaps in a STM. This may also contribute to an unintentional focus on completing one ESD at the expense of a larger number that could be more easily completed.

The current process as it is envisioned in the Natural Resource Conservation Service National Ecological Site Handbook (NESH)[6] is dependent on data to move forward. The requirement of a "final" and "certified" ESD embodied in the current ecological site development process can manifest two opposing, counter-productive philosophies: pursuit of perfection, and "get-'r-done." Under the pursuit of perfection model, the iteration loop in the ESD process is endlessly repeated because there are always additional unknowns about the existence, function, or attributes of states or transitions in an ESD. This situation leads to a type of "analysis paralysis"[9] where a final ESD can never be produced and certified. The alternative, the "get-'r-done" approach, basically short-circuits the iterative loop of the ecological site creation process and marches from beginning to end with whatever data and knowledge happen to exist. This potentially creates ESDs that are incomplete, incorrect, or "copy-and-pasted" from other similar ecological sites. In both approaches, ecological site concepts and STMs become hostage to the development process and its data requirements rather than being supported by it.

STM Creation as Abductive Reasoning

An alternative to the traditional inductive/deductive model for rapidly and accurately creating ecological site concepts and products is called *abductive inference*. In abductive inference, the most likely explanation is proposed for an event or process given an incomplete knowledge of the system, and that explanation is then tested or validated with available information.[8] Abductive inference works best in an iterative setting where inferences are used to create testable hypotheses (deductive) to either confirm or refute the proposed explanations, and the additional knowledge gained is, in turn, used to improve the predictions. A key difference between abductive and inductive/deductive modes of inference lies in the weight or merit given to the possible explanations. In an inductive/deductive mode, a hypothesized attribute or transition is considered suspect until it has been validated by data. In an abductive mode, the same hypothesized attribute or transition would be considered the best possible explanation that is supported by existing knowledge and available data.

The difference between inductive/deductive and abductive inference may seem subtle and largely semantical, but the implications of the difference are important for application of ecological site concepts. In an inductive/deductive approach a hypothesized process or relationship is considered suspect until it has been confirmed through research. With an abductive approach, that same hypothesized relationship is considered to be the best explanation that is supported by existing knowledge and available data until it can be disproved and replaced with a better explanation. In an inductive/deductive mode, draft products are not released for fear they contain errors or incorrect process descriptions. In an abductive mode, draft products are made available to users with the understanding that they are preliminary and can be improved through additional inquiry and observations. Additionally, an important component of a draft product would be a specific statement about what additional inquiry and observations are necessary.

Abductive reasoning is commonly used in other fields. For example, in astrophysics, researchers observe patterns in cosmological data and formulate ideas as to the processes that might give rise to those patterns. Those ideas are crystalized into an explanatory model (which is often published), and then the model is subject to verification by new observations to test its predictions. The models themselves are considered valid and useful if they adequately describe the available data and until they are invalidated by new observations. As a second example, abductive reasoning is often used in healthcare by doctors to make diagnoses based on established symptoms and diagnostics. Treatments are usually prescribed from a limited set of test results from a patient and the outcome monitored to determine if the diagnosis was correct. If the patient fails to get better, more tests may be performed and another diagnosis made. Both examples have evolved for fields where it is not possible either to achieve complete knowledge or to perform experimental manipulations to achieve conclusive evidence in a more direct manner.[10] Abductive reasoning is also the basis for adaptive management of natural resources,[11] and is embodied in the concept of using "best available science" for translating rangeland research into policy and management action.

We propose that the development of ecological site concepts and ESDs is an abductive reasoning task and as such a more iterative approach to their development is needed than what is currently described in the NESH.[6] Under an abductive model, the whole ecological site/STM process becomes iterative and seeks to define concepts/processes that best explain the available data, test those concepts, and refine predictions. Many ecological site specialists recognize the value of and already employ a degree of abductive reasoning in the development of ecological sites and ESDs. However, the current direction in the NESH to develop "final" products and an agency management focus on "job completion" has created a climate that threatens a flexible and iterative approach to creating ecological site products.

The use of abductive reasoning in the ecological site/STM process may also provide stronger encouragement to empower the "technical team" as described in the NESH.[6] Too frequently, it has been observed that where a full technical team (including ranchers and multiagency representation) is inoperative, a single ecological site specialist takes the workload upon their shoulders. The sole-worker approach tends naturally toward inductive/deductive reasoning and easily succumbs to the two opposing philosophies described above—for example, input from multiple and different individuals can be viewed as a threat to the "get-'r-done" urge. However, an abductive approach to iteratively creating ecological site concepts and STMs may increase public acceptance of ecological site/STM products, and provide a better opportunity to incorporate local knowledge into their improvement and validation.[7,12]

We suggest that a revision of the ecological site development processes described in the NESH is needed that establishes a more iterative approach based on abductive inference (Fig. 3). The preliminary stages of the revised process are similar to the existing workflow, and centered around gathering and synthesizing existing information and data to create an initial ecological site concept. From this starting point, an iterative stage begins where an initial ESD and STM are created from available literature, existing data, and expert and local knowledge. Ecological states are identified and described using available data, and transitions between states are established either via documentation (e.g., from existing literature) or postulation (e.g., expert opinion). At each stage in the dynamic development phase of the process, the concepts that have been developed are tested against existing data, or if insufficient data are available, then collection of new data is warranted. Because one role of data in the dynamic development phase is to support or refute the existence or definition of STM components or processes, datasets of differing quality can be useful. Low- or medium-intensity inventory data[6] may provide support for a STM and potentially offer a broader-scale view of variability across an ecological site. Alternatively, high-intensity data[6] may be necessary to fill knowledge gaps about transitions between ecological states or to provide conclusive support for part of an ESD.

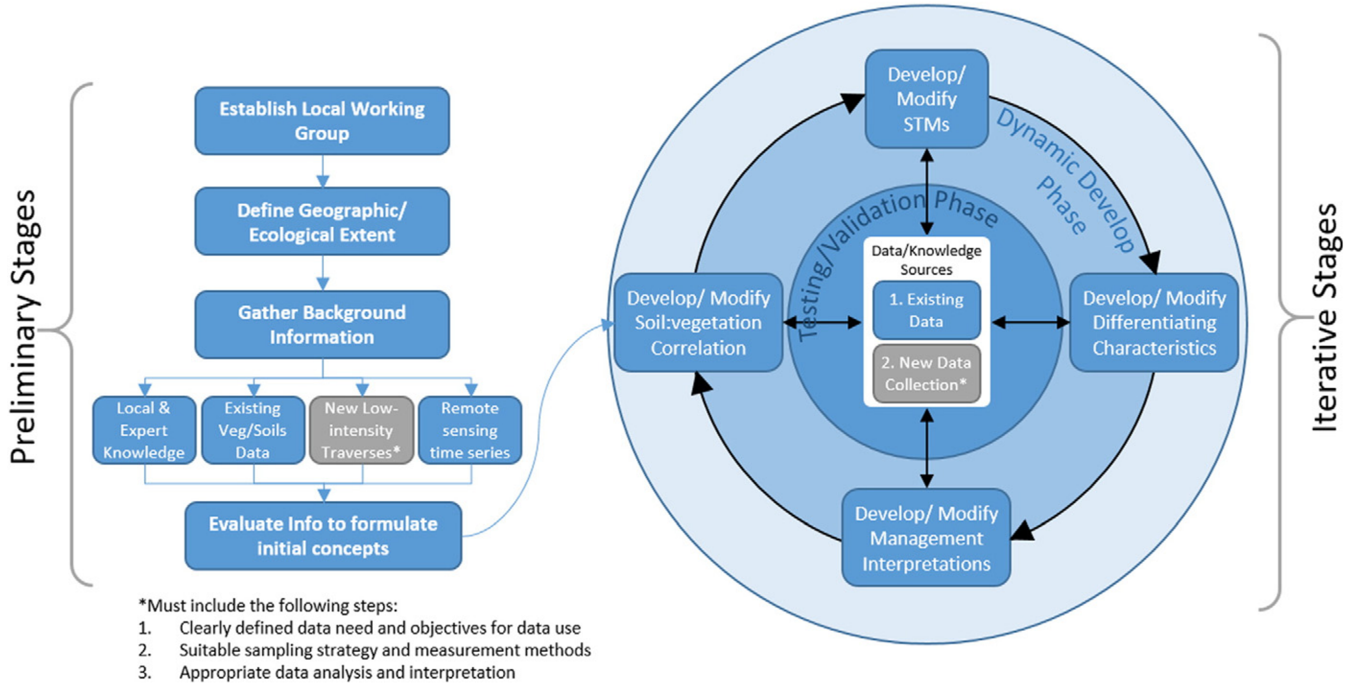

Figure 3. A revised approach to developing ecological site descriptions (ESDs) and state-and-transition models (STMs) based on an abductive inference model. With abductive reasoning, data are used to either confirm or refute the current working knowledge of the system, but the process is iterative. New data (gray boxes) are collected only when existing data are not available or sufficient to confirm an aspect of the model. Because the ESD and STM are constantly being improved and refined based on new observations, there is no final product. Instead, snapshots of the product can be made and subjected to quality control and certification processes as needed. However, the in-development version of the model and its underlying data should always be available and accessible to users, and include recommendations for additional data and standards for contribution to improve the model.

An important concept to this revised ecological site development process is that there is no such thing as a "final" ecological site concept, ESD, or STM—each of these continues to develop over time in response to new knowledge or research. At any point, the ESD or the STM is the best expression of our understanding of how the system works, but is always subject to validation (or invalidation) based on new data and knowledge.

We recognize, of course, the need for quality control in the development of ecological site, and the certification of ecological site concepts, ESDs, and STMs that meet some minimum standards. This can be achieved in the new process model by taking "snapshots" of the ecological site products at a point in time and subjecting them to a review and certification process. While these may be the "approved" versions for some applications, we would argue strongly that the iterative products themselves have tremendous value and should be publicly available. For some ecological sites, achieving the data and knowledge to meet certification standards may take a long time (if it is even achievable), but users may find value in preliminary products with the understanding that some aspects may not be well supported. This is akin to software companies that produce supported versions of their software, but also make available beta versions that represent the latest development stages with the understanding that using a beta version is done at your own risk.

Conclusion

Information embodied in ESDs and STMs is crucial to effective land management, and as such is needed now. There is not time (or money) to employ a traditional research approach (i.e., hypothetico-deductive) to addressing the unknowns in developing and documenting ecological site concepts. Accordingly, an abductive-reasoning approach that relies on best available knowledge and research to develop initial ecological site concepts that are then tested with available data is the quickest and surest way to providing usable products to land managers. Under such an abductive approach, ecological site concepts are never viewed as final, but only the best representation that is supported by available knowledge and data. The natural result of this way of thinking is that products like ESDs and STMs should continually be tested and improved as new data become available.

At the end of the Tootsie Roll Pop commercial, with the boy looking disappointedly at the stick that is all that remains of his sucker, the narrator says, "How many licks *does* it take to get to the Tootsie Roll center of a Tootsie Roll Pop? The world may never know." The current approach to developing ecological sites and ESDs is inefficient, limited in its ability to leverage existing data, and ultimately driving toward an unrealistic goal of final products. Without a more iterative, explanatory approach, the world (or at least the rangeland management community) may never know the full utility of ecological site concepts.

References

1. Karl, J.W., J.E. Herrick, and D. Browning. 2012. A strategy for rangeland management based on best-available knowledge and information. *Rangel Ecol Manag* 65:638-646.
2. Karl, J.W., and J.E. Herrick. 2010. Monitoring and assessment based on ecological sites. *Rangelands* 32:60-64.
3. Karl, J. W., J. E. Herrick, and D. A. Rangeland systems: processes, management and challenges. Springer Verlag. In Press.
4. Moseley, K., P.L. Shaver, H. Sanchez, and B.T. Bestelmeyer. 2010. Ecological site development: a gentle introduction. *Rangelands* 32:16-22.
5. Bestelmeyer, B.T., A.J. Tugel, G.L. Peacock, D.G. Robinett, P.L. Shaver, J.R. Brown, J.E. Herrick, H. Sanchez, and K.M. Havstad. 2009. State-and-transition models for heterogeneous landscapes: a strategy for development and application. *Rangel Ecol Manag* 62:1-15.
6. USDA Natural Resources Conservation Service, 2014. National Ecological Site Handbook. Washington, D.C. 129 p.
7. Knapp, C.N., and M.E. Fernandez-Gimenez. 2009. Understanding change: integrating rancher knowledge into state-and-transition models. *Rangel Ecol Manag* 62:510-521.
8. Douven, I. 2011. In: & Zalta EN, editor. Stanford encyclopedia of philosophy. http://plato.stanford.edu/archives/spr2011/entries/abduction/.
9. Boss, J. 2015. How to overcome the 'analysis paralysis' of decision-making. Forbes. http://www.forbes.com/sites/jeffboss/2015/03/20/how-to-overcome-the-analysis-paralysis-of-decision-making/. Accessed 4 October 2016.
10. Elliott, L.P., and B.W. Brook. 2007. Revisiting Chamberlin: multiple working hypotheses for the 21st century. *Bioscience* 57:608.
11. Walters, C.J., and C.S. Holling. 1990. Large-scale management experiments and learning by doing. *Ecology* 71:2060-2068.
12. Knapp, C.N., M.E. Fernandez-Gimenez, and E. Kachergis. 2010. The role of local knowledge in state-and-transition model development. *Rangelands* 32:31-36.

Authors are Research Ecologist, USDA Agricultural Research Service, Jornada Experimental Range, Las Cruces, New Mexico, USA (Karl, jason.karl@ars.usda.gov) and Range Management Specialist, USDA Natural Resources Conservation Service, Las Cruces, New Mexico, USA (Talbot).