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Needs Assessment of Coastal Land Managers for Drought Onset Indicators in the Southeastern United States

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ABSTRACT

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The ability to detect the onset of drought is important to coastal resource managers because the knowledge enhances preparedness and mitigation. Existing drought indicators, however, were generally designed with agricultural, hydrological, meteorological, socio-economic, or wildfire management in mind and generally quantify deficits in freshwater availability. It is unclear whether coastal resource managers find existing indicators adequate for managing coastal resources and, if not, what information would be most useful to manage resources under threat of drought. A needs assessment was conducted with 30 land managers and natural resource specialists of the coastal Carolinas region to enhance the understanding of drought indicators and to comprehend the indicators' utility for managing coastal natural resources. Eighty-three percent of participants believed that early drought detection was important for their management efforts, yet only 33% were aware of existing drought indicators. Half of the participants stated that drought indicators needed to be specifically focused on a particular kind of habitat, but 90% thought that a single index could be useful for multiple coastal habitats with broad similarities. All participants who stated a current need for an early-warning drought indicator (83%) emphasized indicator parameters that reflected both freshwater availability and impacts on ecological resources, but 86% of the participants indicated that they may not have the resources to collect such data. The results revealed common priorities and concerns among coastal resource managers and exposed opportunities to incorporate parameters of shared interest into a drought indicator tailored to the early detection of drought through the inclusion of ecological parameters.

ADDITIONAL INDEX WORDS: *Resource management, drought index, interview, coastal Carolinas.*

INTRODUCTION

Droughts are generally expected to increase in both frequency and magnitude (IPCC, 2012; Jentsch, Kreyling, and Beierkuhnlein, 2007), and the development of drought indicators has enhanced the ability to detect spatial-temporal trends in drought incidence and magnitude (Quiring, 2009) as data availability increases (Bales, 2014). Traditionally, drought has been defined within one of four contexts, and different metrics characterize drought within each context. These contexts include agricultural drought (characterized by soil moisture and crop yields), hydrological drought (characterized by freshwater supply via stream flow and groundwater levels), meteorological drought (characterized by atmospheric conditions and precipitation), and socio-economic drought (characterized by the influence of drought on the supply and demand of an economic good) (American Meteorological Society, 1997; Hao and AghaKouchak, 2013; Heim, Jr., 2002; Shukla, Steinemann, and Lettenmaier, 2011). These categories of drought can reflect impacts of drought on different time scales. For example, a precipitation deficit (meteorological drought) may be detected after several weeks, whereas a significant drawdown of groundwater levels (hydrological drought) may be conspicuous only after several months (Heim, Jr., 2002).

Increasingly, scientists have recognized the necessity of defining drought within an ecological context (Lackstrom *et al.,* 2014; Lake, 2003, 2011). An ecological drought represents the influence of water stress on the structure and function of ecological habitats (van der Molen *et al.,* 2011). A recent review of the literature revealed that changes in the magnitude, timing, and frequency of precipitation events can have important implications on the performance of plants in ecological settings even when the net amount of precipitation remains unchanged (Anderegg, Kane, and Anderegg, 2013). Moreover, the particular consequences of extreme precipitation patterns can depend on ecological context. For example, gross primary production and net ecosystem productivity of shrublands and forests at drier sites have been found to decline more strongly in response to seasonal changes in the distribution of rainfall than shrublands and forests at wetter sites (Ross *et al.,* 2012). Tilman and Downing (1994) also demonstrated that the occurrence of drought affects grasslands with a greater diversity of plant species present to a lesser extent than grasslands with fewer plant species. Both mean annual precipitation and the functional diversity of plants present in grassland sites in the United States were thought to influence how similar levels of drought affected net primary production at a site (Knapp *et al.,* 2015).

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The ability to detect the onset of drought is essential in resource management because it provides the knowledge that allows managers to anticipate impacts to resources and provides an opportunity to implement risk management strategies (Altman, 2013; Wilhite, 2001). A number of drought indices exist to aid in the detection of traditional drought classifications (see Choi *et al*. [2013], Heim, Jr. [2002], and Vicente-Serrano *et al*. [2012] for in-depth reviews). Common indices include the Palmer Drought Severity Index (PDSI; Palmer, 1965), the Evaporative Stress Index (ESI; Anderson *et al.,* 2007), and the Keetch-Byram Drought Index (Keetch and Byram, 1968). The PDSI was a seminal advancement of drought detection and is based on a precipitation and temperature-driven water-balance model. Though no model is without limitations (Alley, 1984; Guttman, 1998), the PDSI is perhaps the most widely utilized indicator for detecting agricultural drought (Choi *et al*., 2013; Vicente-Serrano, Beguería, and López-Moreno, 2010). While the PDSI was based on climatological parameters, the ESI detects drought by deriving a model based on an energy balance where the evaporation potential of land surfaces under various vegetative cover are incorporated via remote sensing (Anderson *et al.,* 2007; Choi *et al.,* 2013). Alternatively, the Keetch-Byram Drought Index is widely used to assess the potential for wildfire by using a daily water balance based on evapotranspiration, precipitation, and cumulative soil moisture levels. Other indices, such as the Standardized Precipitation Index (based on precipitation) and its variant, the Standardized Precipitation Evapotranspiration Index (accounting for temperature), have increased comparability of drought conditions in different regions and time scales (Livada and Assimakopoulos 2007; Ntale and Gan, 2003; Vicente-Serrano, Beguería, and López-Moreno, 2010). While these indices have significantly enhanced the ability to detect the onset of drought, they do not assess the potential impacts of ecological drought. Instead, current drought indices offer the user a quantification of a precipitation deficit. While informative, such a measure may not provide an indication of the ecological consequences of the water deficit. A recent study (Vicente-Serrano *et al.,* 2012) examining correlations between existing drought indices and some metrics of ecological response (*e.g*., tree growth and wheat production) found rather modest correlations (generally between 0.15 and 0.45).

Drought and drought impacts in coastal regions can be quite different from otherwise similar inland locations. Estuaries associated with large alluvial rivers depend on the freshwater flow and loads for maintenance of the habitat variability associated with salinity gradients that are needed by many species (Anderson and Lockaby, 2012; Hupp, 2000; Perry and Atkinson, 1997; Rozas and Odum, 1987). Significant reduction in flows and loads caused by drought in the inland watershed can affect ecosystem functions (Gilbert, Lackstrom, and Tufford, 2012), especially in locations with large tidal amplitude. High-salinity, well-mixed estuaries are less dependent on freshwater inflow, but the small streams that drain into them often support freshwater or brackish wetlands that are habitat for diverse biota (Dame *et al*., 2000). Coastal economies, from tourism to commercial fisheries, often depend on the ecological results of these dynamics as well.

Similarly, weather patterns along the coastal Carolinas can be quite different from nearby areas further inland. These coasts often receive more precipitation because of moist winds coming off the coastal ocean. Depending on the specific location, a coast may be subject to tropical storm activity that brings intense and sometimes long duration precipitation events (Diem, 2006; Henderson and Vega, 1996). Though episodic and infrequent, their occurrence can have profound impacts on coastal areas (Brun and Barros, 2013; Conner and Inabinette, 2003; Conner *et al*., 2014). Therefore, upland ecosystems in coastal zones must be adapted to different moisture dynamics than inland systems, and a seasonal or longer term significant reduction in either of these precipitation sources may affect ecosystem processes (Dai *et al*., 2010; Epps *et al*., 2013).

The SE Coastal Plain, the site of this study, is part of one of the largest physiographic provinces in the eastern United States, which includes the coastal inland of the Atlantic, Gulf of Mexico, and the Mississippi Alluvial Valley. The characteristic physiography of broad, low-gradient land surface adjacent to the coastal ocean also occurs extensively on other continents. Variations among locations are significant, but there are physical drivers that are similar among them (*e.g.,* upland runoff, salinity intrusion, flooding potential), all aspects that suggest commonalities when thinking about natural resource management.

These considerations suggest that the needs for an ecological drought indicator by resource managers be assessed to determine whether and how an early-warning indicator of ecological drought is desirable. Doing so will require knowledge of the stated needs of resource managers and the drought parameters they consider to be most important toward their management efforts. By conducting a needs assessment, this study can begin to identify common themes and to increase the utility of an early detection index that emphasizes ecological drought.

Open-ended, semistructured interviews were conducted among land managers in the coastal Carolinas to elucidate the attitudes, preferences, and stated needs regarding the early detection of drought. The focus of the present study was on the need for ecological drought indicators in coastal areas because coastal areas represent a patchwork of diverse habitats that are exposed to frequent drought (Gilbert, Lackstrom, and Tufford, 2012; Seager, Tzanova, and Nakamura, 2009; USGS Staff, 2002) and there is an increasing perception that there may be a need for the development of an ecological drought indicator for the coastal Carolinas (Lackstrom *et al.,* 2014; Petes *et al.,* 2014). Furthermore, there is a high potential for drought to affect coastal ecological areas by not only changing the availability of freshwater but also by promoting salinity intrusion into aquifers and soils and by influencing the location of the saltwater–freshwater interface within coastal tributaries (Aguilar *et al.,* 2012).

METHODS

A needs assessment was conducted to elicit information regarding drought concerns and the applicability of early drought indicators from land managers along the North and South Carolina coasts. The study area of this investigation was the coastal plains and margins of North and South Carolina. This area was defined using U.S. EPA Level IV Ecoregions and was delineated using ArcMap 10.1 (Figure 1).

Table 1. *Responses of 30 participants when asked which natural resources were most sensitive to drought. Values indicate the number of responses, where participants were able to provide multiple answers. Terrestrial = individuals who focus on terrestrial habitats (*n = 8*), Aquatic = individuals focused on aquatic habitats (*n = 10*), Both = individuals who focus on terrestrial and aquatic habitats with equal emphasis (*n = 12*). The All column refers to the sum of all responses regardless of the type of land participants managed.*

Resource	Terrestrial	Aquatic	Both	All
Habitat				
Isolated wetlands	3	3	3	9
(Pocosins)	4	0	1	5
(Cypress/Tupelo marsh)	0	1	1	2
(Organic soils)	5	0	4	9
Brackish/salt wetlands	0	1	0	1
Lakes/ponds	1	1	1	3
Streams	0	1	1	2
General pine community	0	0	1	1
Pine uplands	1	0	0	1
Pine savannah	1	0	0	1
Agricultural area	0	0	1	1
Totals	15	7	13	35
Vegetation				
General plant community	0	1	0	1
Wetland plants	0	2	3	5
Aquatic vegetation	0	1	0	1
Riparian vegetation	0	1	0	1
Food abundance for game spp.	1	0	0	1
Totals	1	5	3	9
Wildlife				
Fisheries	0	2	0	2
Amphibians	0	0	1	1
Totals	0	2	1	3
Abiotic				
Fuel loads	0	0	1	1
Freshwater availability	0	1	0	1
Totals	0	1	1	2

To identify potential interview participants, a list of managed areas (along with their respective geospatial coordinates) in North and South Carolina were compiled from two publically available online databases. These databases included the North Carolina Department of Environment and Natural Resources (NCDENR) Natural Heritage Program (Managed Areas, Natural Areas, Protected Areas) and the South Carolina Department of Natural Resources Managed Lands. The databases provided a comprehensive list of managed areas regardless of ownership (*i.e.* public, private) or agency stewardship (*i.e.* local, state, federal). A subportion of these managed areas was purposefully selected based on their collective spatial representation of the study area, habitat heterogeneity among the areas, and diversity of organizations that manage the areas. Contact information for managers and specialists of these respective areas were obtained online, and individual solicitation emails were sent to 88 individuals who met the selection criteria that requested participation in structured phone interviews. The interviews comprised 20 questions (Supplementary Material Table A) that were based on five major themes: (1) Drought Concerns & Information Needs, (2) Resource Sensitivity, (3) Drought Parameters & Data Collection, (4) Utility & Relevance of Indicators, and (5) Indicator Development.

Responses were transcribed in real time and then coded categorically for thematic analysis so that the diversity and repetition among common themes were readily identifiable. The 30 participants are categorized based on their emphasis on broad habitat types (*e.g.*, terrestrial, aquatic, or both).

RESULTS

Thirty of the 88 individuals who met the selection criteria and were contacted for the needs assessment volunteered to participate, representing a response rate of 34%. Participation was greatest at the state level (57%), relative to federal and nonprofit sector participation (30% and 13%, respectively) for those interviewed. Of the 30 participants, 14 represented managerial positions, and 16 were resource specialists. Participant backgrounds represented biology/ecology ($n = 21$), hydrology ($n = 5$), and fire management ($n = 4$). Specific backgrounds ranged from botany, climate change adaptation, coastal resource management, fire management, fluvial dynamics, silviculture, wetlands, and wildlife management. It is important to note that all participants managed or otherwise investigated multiple habitat types within their managed area. Eight respondents focused on terrestrial habitats, 10 focused on aquatic habitats, and 12 focused on both with equal stated emphasis. Among the aquatic-focused participants, eight emphasized freshwater, four emphasized salt/brackish environments, and 10 emphasized both fresh- and saltwater environments equally.

Drought Concerns and Information Needs

Fifty percent of respondents explicitly stated that drought was a specific management concern of their respective land (27% reported that drought was indirectly managed, while 23% indicated that it was not of concern) and that there was a current need for drought-related data (33% indicated there was somewhat of a need, and 17% reported no need). The need for drought-related data was expressed to a similar degree by individuals who managed aquatic (60% of eight respondents), terrestrial (50% of 10 respondents), or aquatic and terrestrial resources (41% of 12 respondents). When asked whether there might be a greater need for drought information in the future, 57% of participants responded affirmatively, 33% were unsure, and 10% reported there would not likely be a need. Here, individuals who primarily manage only aquatic habitats were more likely to answer affirmatively (70% of eight respondents) than those who manage both aquatic and terrestrial habitats (58.3% of 12 respondents) or those that focus on the management of only terrestrial habitats (37.5% of 10 respondents). Participants who focused their management efforts on salt/brackish aquatic environments stated the least need for drought detection, as three out of the four participants who primarily manage salt/brackish environments stated drought was not a management concern.

Resource Sensitivity

Participants were asked which natural resources under their stewardship were most sensitive to drought and were allowed to offer multiple open-ended responses (Table 1). Regardless of background, jurisdiction, or emphasis on terrestrial or aquatic habitat, a conspicuous emphasis on freshwater wetland habitat and the saturation and salinity of organic soils (which promotes

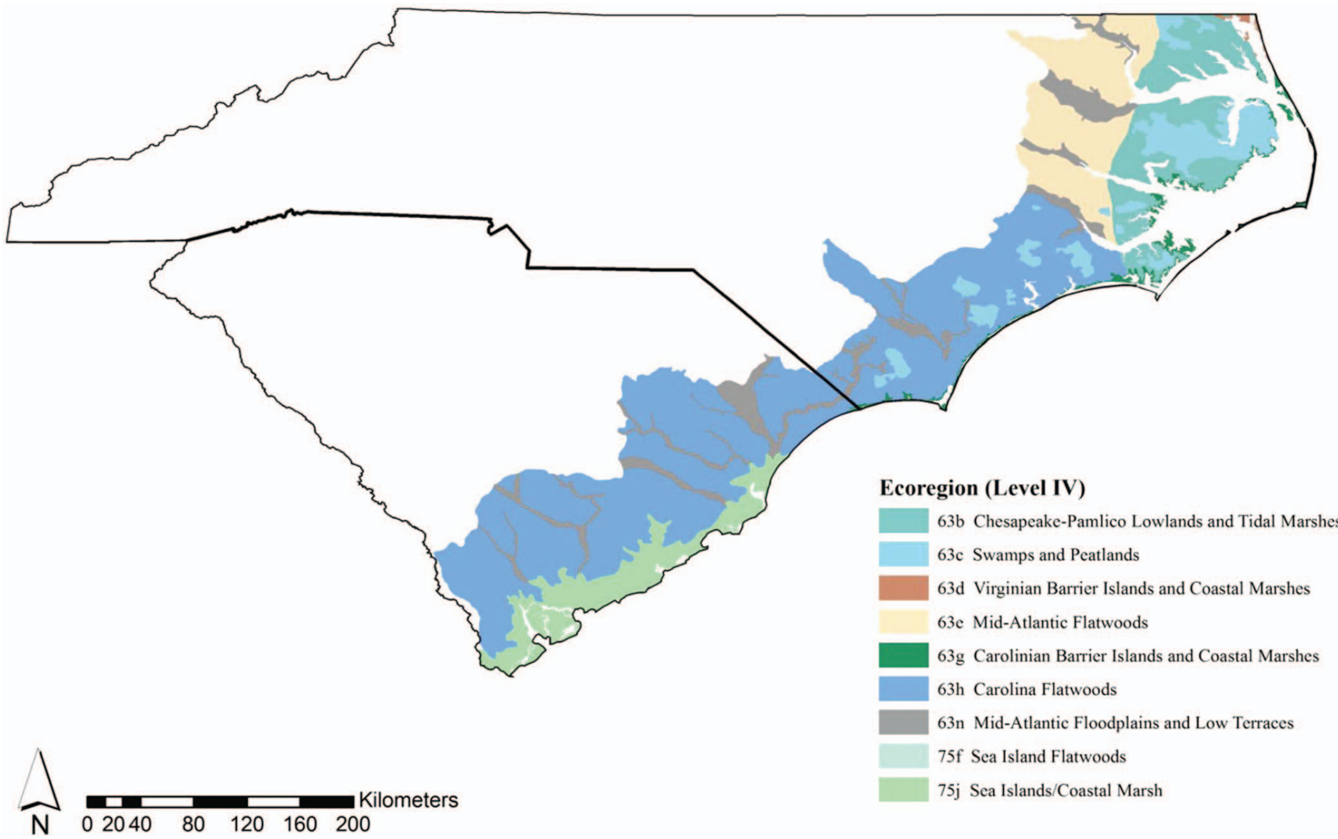

Figure 1. Delineation of study area. The illustrated U.S. EPA Level IV Ecoregions collectively represent the definition of "coastal Carolinas" assumed in the present study.

wildfire vulnerability) existed. Specifically, the desiccation of organic soil and isolated wetlands were each invoked on nine instances, whereas pocosins ($n = 5$) and wetland-dependent plants ($n = 5$) also represented recurring answers within the freshwater wetland theme. While freshwater wetland habitats were described as being particularly sensitive to drought (Table 1), anecdotal impacts of drought varied among respondents. Managers offered a wide variety of impacts on the ecological systems that they manage, but most focused on water-availability parameters (*e.g.*, soil moisture, increases in salinity, freshwater input), greater vulnerability for fires, and reduced performance of wetland plants (Figure 2).

Drought Parameters and Data Collection

Participants differed markedly in their opinion about which variables are necessary to detect the onset of drought (Figure 3). Nine participants currently monitor all variables that they believe would allow them to detect the onset of drought and provide such data publically. The remaining 21 participants who do not monitor variables they considered most informative for detecting drought emphasized the need for monitoring hydrological and soil parameters. Specifically, the need for data on freshwater availability, precipitation patterns at small spatial scales, soil moisture, and salinity intrusion into both terrestrial and aquatic habitats were most often invoked and reaffirmed the themes needed to evaluate the impact of drought on freshwater wetlands (Figure 3). Participants offered diverse responses when describing specific data collection efforts that would facilitate their ability to detect drought (Table 2). The primary factors that inhibited the participants from collecting these data were lack of manpower (12 responses), lack of budget funds (11 responses), and an inability to sample large spatial scales (seven responses).

Utility and Relevance of Drought Indicator

Without providing respondents with examples, respondents were asked whether they were aware of any existing drought indicator. Only 10 (seven of those whose work focused on terrestrial habitats) of the 30 respondents specifically stated an awareness of formal drought indicators. In all 10 responses, respondents stated an awareness of the Keetch-Byram Drought Index. Additionally, the Energy Release Component and the Buildup Index, which are both measures of wildfire parameters and not drought per se, were each mentioned on two occasions.

Nearly all (28 of 30) respondents stated that they believed a drought indicator would be useful for their managed lands as long as there was some degree of habitat-specific dependency built into the indicator. Participants were divided in their opinions of whether a particular drought indicator needed to

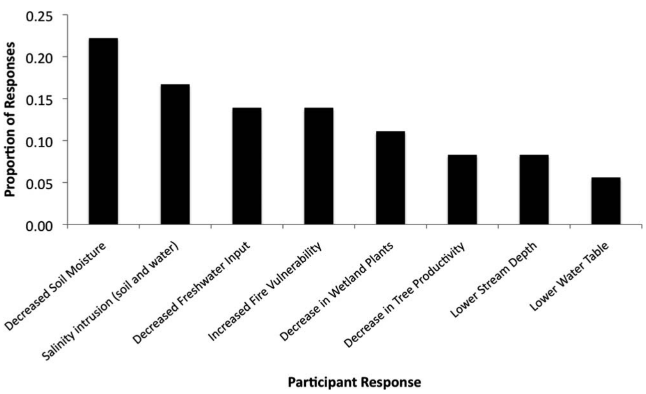

Figure 2. Proportion of responses ($n = 36$) when asked to describe the impact of drought on managed resources. Note: Each participant ($n = 30$) was allowed to provide multiple answers.

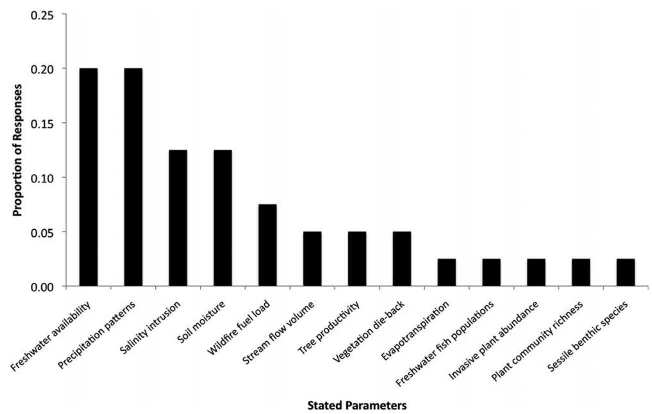

Figure 3. Responses of participants ($n = 30$) when asked which parameters would provide them with an early detection of drought conditions. Note: Participants were allowed to provide multiple answers, and the number of responses is not cumulative to participant sample size.

be tied to a specific type of habitat (53% yes, 47% no), but the opinions varied depending on the type(s) of resources that they managed. The majority of individuals who focused on the management of aquatic habitats were more likely (eight *vs*. two individuals) to indicate that drought indicators needed to be tied to a specific habitat, while individuals who focused on the management of terrestrial habitats were equally divided (four *vs*. four) in their opinions on this question. Respondents who managed both terrestrial and aquatic resources were less likely (four *vs*. eight individuals) to state that an indicator would need to be habitat specific. For those respondents who suggested that drought indicators were habitat specific, the stated reasons included the following: freshwater input sources vary among habitats, weather patterns are not necessarily consistent among spatial scales, impacts of drought are diverse, and soil composition varies among areas. Nevertheless, when asked whether drought indicators could be applicable in multiple coastal habitats (*i.e.* throughout the study area), the majority of participants responded affirmatively (90%) with the caveat that indicator variables were applicable among different terrestrial or aquatic habitat types. For example, soil salinity is a parameter that can be quantified in any terrestrial habitat. There was no meaningful variation in these responses according to an emphasis on terrestrial or aquatic habitat.

Indicator Development

Participants were provided with an open opportunity to suggest the most useful characteristics that they felt an early-warning drought indicator would ideally exhibit. Responses were diverse, and 37% of all participants were unable to specify a characteristic. The remaining 63% of participants offered a wide range of characteristics that failed to reveal a discernable consensus or pattern (Table 3). These individuals collectively offered eight unique characteristics with a weak emphasis on sampling attributes. The most commonly repeated responses included the ability to use indicator variables to predict drought severity, the ability to extrapolate index values, and the incorporation of plant species sensitivity to water availability. The proceeding question asked participants to identify other variables or characteristics they desired in an indicator, though not necessarily the single most important variable (Table 3). The most common response included the inclusion of organic soil saturation (eight responses), the inclusion of aquatic salinity concentration (six responses), and the incorporation of wetland plant sensitivity (six responses). There was a general focus on incorporating abiotic variables (32 responses), whereas sampling characteristics (*e.g.*, ability to extrapolate index values, predictive ability) and biotic variables were suggested on 13 and 12 occasions, respectively.

DISCUSSION

A majority of the resource managers believe that there is utility in the availability of an ecological drought indicator if one were available. A few respondents, however, stated that early drought detection was not necessary in their management activities and offered two reasons for this opinion.

First, the resource managers believed that their managed resources were not significantly affected by drought (*i.e.* there was no need). These individuals primarily managed forested habitat and Carolina Bay wetlands, so it could be determined that an ecological drought indicator is less important for the management of these kinds of habitats. Nonetheless, the overwhelming majority of those who managed similar habitats believed that these habitats are particularly vulnerable to drought and that these differences in opinion may reflect a lack of understanding of how drought could affect these coastal habitats.

Second, some resource managers thought that there are no mitigating actions that could be implemented to ameliorate drought (*i.e.* drought detection was not actionable). Though this may be true, an indicator of ecological drought may still be useful to resource managers. Managers may not be able to mitigate the effects of a particular drought, but perhaps they could allocate resources to systems or places that are less sensitive to drought but are vulnerable to other stressors for which there are actionable measures that the manager can

Table 2. *Responses of participants when asked what types of data collection would be useful in their management efforts to detect drought. Note that the Number of Responses is not cumulative to sample size (n = 30) and that participants could respond with multiple answers. The All column refers to the sum of all responses regardless of the type of land participants managed.*

Response	Terrestrial	Aquatic	Both	All
Aquatic				
Quality/salinity	0	3	1	4
Water table	2	2	2	6
Freshwater availability	0	1	1	2
Totals	2	6	4	12
Vegetation				
Invasive plants	1	0	0	1
Tree productivity	1	0	0	1
Wetland plants	1	0	2	3
Plant vulnerability	1	1	0	2
Long-term plant community	1	0	1	2
Totals	5	1	3	9
Wildlife				
Game species abundance	0	0	1	1
Shellfish	0	1	0	1
Totals	0	1	1	2
Abiotic/ Sampling				
Regional geology	0	1	1	2
Soil moisture	4	1	1	6
Soil Salinity	0	0	1	1
Short-term rainfall variability	1	3	1	5
Applicable to large spatial scale	1	1	1	3
Applicable to fine/local scale	0	0	1	1
Totals	6	6	6	18
None/Not useful	0	1	1	2

Table 3. *Responses of all participants when asked to identify the most important characteristics of a drought indicator and to identify the additional useful characteristics/variables of an indicator. Note that the Number of Responses is not cumulative to sample size (n = 30) and that participants could respond with multiple answers.*

Stated Preferences	Number of Responses
Most Important Indicator Characteristics	
Ability to predict drought duration	2
Ability to predict eminent drought occurrence	3
Incorporate regional groundwater data	2
Seasonal variability in precipitation	2
Regional scale of drought	5
Incorporate plant species sensitivity	3
Applicable on local scale	3
Incorporate regional coastal geology	1
Not sure	11
Additional Useful Indicator Variables	
Abiotic	
Organic soil saturation	8
Precipitation patterns	5
Wildfire susceptibility	4
Water salinity and quality	6
Water-table level	5
Soil salinity	3
Coastal geology	1
Biotic	
Amphibian response	1
Tree mortality	3
Invasive plant species	1
Wetland plant composition and abundance	6
Upstream eutrophication	1
Sampling	
Drought severity	5
Drought duration	5
Ability to extrapolate drought index	2
Monthly data collection on index variables	1

implement. Knowledge of how particular properties of an ecological system vary with particular levels of a drought indicator could also aid managers in knowing the extent to which an observed change in an ecological system is attributable to drought or some other stressor for which there may be actionable measures. Longer term temporal trends of indicator values could also aide managers in strategic planning as future climate patterns may present scenarios in which a full recovery to predisturbance habitat may not be practical in the near term (Duarte *et al*., 2013; Hilderbrand, Watts, and Randle, 2005).

This survey did not specifically ask managers to comment on how they would incorporate information from ecological drought indicators into their specific management decisions given the multitude of other considerations that must also be taken into account. Such information would be very useful in understanding the ways in which resource managers make decisions on managing properties that are susceptible to drought. The fact that 90% of respondents anticipated a potential future need for drought detection, however, implies that the detection is an important factor for consideration by most managers. Future studies that examine how managers may alter their management decisions on the basis of drought indicators would be very useful.

Despite the stated current need for drought detection by 83% of the resource managers (and 90% anticipating a potential future need), only 10 managers had knowledge of existing drought indicators. In these cases, all individuals referenced the Keetch-Byram Drought Index (an indicator of wildfire potential) or the Energy Release Component (an indication of how hot a wildfire could burn) in the context of fire management or silviculture. These indicators likely meet some of the needs of these managers but perhaps not all. For example, individuals focused on silviculture expressed interest in the impacts of drought on growth and mortality of trees; the indicators that they currently utilize may not provide much insight into this kind of response to drought.

Managers expressing a need for an ecological drought indicator who simply lack familiarity with drought indicators does not necessarily suggest that existing indicators are not useful to them. Most respondents indicated that the greatest impacts of drought that they observed concentrated on availability of water and that the most important parameters necessary for early detection of drought also focused on water availability. Subsequently, it may be the case that individuals who stated a need for an early-warning drought indicator yet lack familiarity with any existing indicator would benefit from increased awareness of indicators that are currently available. This, in turn, suggests that increased outreach may be needed to expose managers and resource specialists to the information that current indicators could provide them. Existing drought indices appear to satisfy this basic need, but nearly all respondents thought that current drought indicators may have limited utility because the indicators do not explicitly incorporate direct information about the consequences to the ecological resources. Indices that will be most useful to resource managers will be those indices for which there is a clear connection between index values and the status of the biological resources that they manage. Furthermore, indicators that account for water availability as assessed over multiple time scales would be useful given that recent work by Aguilar *et al*. (2012) has demonstrated that short-term (30-day) precipitation totals play a more important role in determining net primary production in coastal areas during dry years but not during wet years.

Managers also identified a number of other aspects, including salinity, that they believe will limit the applicability of existing drought indicators in describing potential impacts on ecological resources. Many managers identified that drought-induced changes in the extent of salt-water intrusion or the location of the salt-water/freshwater boundary in tidal areas can have significant ecological consequences. Consequently, ecological drought indices that incorporate information on salinity would be a useful addition to the suite of tools that resource managers have to manage coastal natural resources. Though no resource managers explicitly emphasized the importance of species diversity for assessing drought, ecologists are increasingly recognizing that plant biodiversity could minimize the consequences of drought on primary productivity (Díaz and Cabido, 2001; Hallet *et al.,* 2014; Knapp *et al*., 2015; Tilman and Downing, 1994). Inclusion of a metric of species diversity into a drought index may also facilitate the identification of which locations may be most impacted by drought.

Practical Concerns of Drought Indicators

The most common concerns among respondents regarding the use of a drought indicator included the inability to collect necessary data because of practical constraints, the broad spatial gaps in data that limit extrapolation, and the extent to which an indicator was relevant among neighboring habitat types. Interpretation of these repeated responses provides several opportunities to mitigate these concerns.

Data collection efforts could be coordinated among managers who supervise similar habitats. An overwhelming majority of respondents (87%) stated that data collected from their management efforts is publically available through an online database or by request. This suggests that if managers collected data needed for the indicator, then data resolution may improve and could increase reliability in extrapolating indicator values. The reliability of extrapolation was invoked on numerous occurrences by managers, regardless of their area of expertise or management objectives.

Ecological variables, such as soil salinity, that are common among habitats could become a focus. Habitat specificity of indicator variables was a significant concern among managers because they often manage multiple coastal habitat types within a larger area.

Selecting input parameters that coincide with management plans could promote indicator relevancy. The inclusion of such variables increases relevancy of the indicator to managers and thus increases the likelihood of regular use of the indicator. In turn, systematic use would provide resource managers with valuable background data that could be used to reveal trends in indicator values and the parameters themselves.

Discrepancy and Commonalities

One might expect that individuals with specialized management objectives would offer unique answers when asked what drought-related variables were most informative for drought detection. Indeed, discipline-specific responses were occasionally offered. For example, hydrologists who focus on surface and groundwater emphasized that intermittent stream depth, desiccation at stream origins, and regional water-table drawdown were most important for determining drought detection. While certainly informative, the relevance of these particular variables was not explicitly shared, for example, among plant community ecologists and fire managers. Nevertheless, far more common were responses among interviewees that overlapped, regardless of the respondent's discipline or background. For instance, soil moisture content and soil salinity were among the leading answers provided when respondents were asked which variables would be most important to include in an early-warning drought indicator. Respondents with different backgrounds offered these responses but used distinct rationales. For instance, fire managers stated that both variables promote wildfire potential by increasing the combustibility of fuel loads through vegetation dieback. Plant ecologists also stated the importance of soil moisture and salinity because of their influence on plant community composition and structure. While it may be unlikely that a single indicator could comprehensively satisfy the needs of managers who steward diverse lands for various priorities, the overlap of these responses from managers suggests that opportunities exist to develop an ecologically based early-warning drought indicator that provides broad utility.

CONCLUSIONS

This work revealed that most coastal resource managers see great value in knowing drought conditions for the properties that they manage, but most also indicated lack of familiarity with existing drought indicators that could be of some use to them. Clearly, greater effort is needed to apprise resource managers of existing drought indicators.

This study also revealed that resource managers have determined that existing drought indicators lack information about important factors that play an important role in affecting how the properties that they manage will respond to drought. Given the diversity of respondent backgrounds and management objectives, it is not likely possible to develop an indicator that can incorporate all desires; however, these results show that common ground exists among resource managers throughout the coastal Carolinas. Specifically, an ecological drought indicator that incorporates salinity intrusion and vegetative parameters of stress (particularly wetland-dependent species) was found to be most useful to the interviewees. The informativeness of such an indicator is increased when these variables are represented by data that is publically available. This study is a critical first step toward identifying variables and constraints that are commonly important for many land managers in assessing ecological drought in coastal systems. In light of these responses, current efforts are focused on the development of a drought index that incorporates information on salinity and ecological properties of estuarine systems to better understand ecological drought in coastal systems. As this index is developed and tested, it will be imperative to reach out to resource managers and inform them about this and other indices of drought. Future studies can then evaluate how managers could incorporate this information into their management decisions.

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LITERATURE CITED

Aguilar, C.; Zinnert, J.C.; Polo, M., and Young, D., 2012. NDVI as an indicator for changes in water availability to woody vegetation. *Ecological Indicators,* 23, 290–300.

Alley, W.M., 1984. The Palmer Drought Severity Index: Limitations and assumptions. *Journal of Climate and Applied Meteorology,* 23(7), 1100–1109.

Altman, E.N., 2013. Drought Indices in Decision-Making Process of Drought Management. Charleston, South Carolina: University of South Carolina, Master's thesis, 71p.

American Meteorological Society, 1997. Meteorological drought-policy statement. *Bulletin of the American Meteorological Soc*iety, 78, 847–849.

Anderegg, W.R.L.; Kane, J.M., and Anderegg L.D.L., 2013. Consequences of widespread tree mortality triggered by drought and temperature stress. *Nature Climate Change,* 3(1), 30–36.

Anderson, C.J. and Lockaby, B.G., 2012. Seasonal patterns of river connectivity and saltwater intrusion in tidal freshwater forested wetlands. *River Research and Applications,* 28(7), 814–826.

Anderson, M.; Norman, J.; Mecikalski, J.; Otkin, J., and Kustas, W., 2007. A climatological study of evapotranspiration and moisture stress across the continental United States based on thermal remote sensing: 1. Model formulation. *Journal of Geophysical Research: Atmospheres (1984-2012),* 112, D10117. doi:10.1029/2006JD007506

Bales, J.D., 2014. Progress in data collection and dissemination in water resources, 1974–2014. *Water Resources Impact*, 16(3), 18–23.

Brun, J. and Barros, A.P., 2013. Vegetation activity monitoring as an indicator of eco-hydrological impacts of extreme events in the southeastern USA. *International Journal of Remote Sensing*, 34(2), 519–544.

Choi, M.; Jacobs, J.; Anderson, M., and Bosch, D., 2013. Evaluation of drought indices via remotely sensed data with hydrological variables. *Journal of Hydrology,* 476, 265–272.

Conner, W. and Inabinette, L.W., 2003. Tree growth in three South Carolina (USA) swamps after Hurricane Hugo. *Forest Ecology and Management*, 182(1), 371–380.

Conner, W.H.; Duberstein, J.A.; Day J.W., and Hutchinson, S., 2014. Impacts of changing hydrology and hurricanes on forest structure and growth along a flooding/elevation gradient in a south Louisiana forested wetland from 1986 to 2009. *Wetlands*, 34(4), 803–814.

Dai, Z.; Trettin, C.C.; Li, C.; Amatya, D.M.; Sun, G., and Li, H., 2010. Sensitivity of stream flow and water table depth to potential climatic variability in a coastal forested watershed. *Journal of the American Water Resources Association*, 46(5), 1036–1048.

Dame, R.; Alber, M.; Allen, D.; Mallin, M.; Montague, C.; Lewitus, A.J.; Chalmers, A.; Gardner, R.; Gilman, C.; Kjerfve, B.; Pinckney, J., and Smith, N,. 2000. Estuaries of the south Atlantic coast of North America: Their geographical signatures. *Estuaries,* 23(6), 793–819.

Díaz, S. and Cabido, M., 2001. Vive la différence: Plant functional diversity matters to ecosystem processes. *Trends in Ecology and Evolution,* 16(11), 646–655.

Diem, J.E., 2006. Synoptic-scale controls of summer precipitation in the Southeastern United States. *Journal of Climate*, 19(4), 613–621.

Duarte, C.M.; Borja, A.; Carstensen, J.; Elliott, M.; Krause-Jensen, D., and Marbà, N., 2013. Paradigms in the recovery of estuarine and coastal ecosystems. *Estuaries and Coasts,* 32(4), 1–11.

Epps, T.H.; Hitchcock, D.R.; Jayakaran, A.D.; Loflin, D.R.; Williams, T.M., and Amatya, D.M., 2013. Characterization of storm flow dynamics of headwater streams in the South Carolina lower Coastal Plain. *Journal of the American Water Resources Association,* 49(1), 76–89.

Gilbert, S.; Lackstrom, K., and Tufford, D., 2012. The Impact of Drought on Coastal Ecosystems in the Carolinas: State of Knowledge Report. *Columbia, South Carolina: University of South Carolina, Research Report 2012 01, Carolinas Integrated Sciences and Assessments*, 67p.

Guttman, N.B., 1998. Comparing the Palmer Drought Index and the Standardized Precipitation Index. *Journal of the American Water Resources Association,* 34(1), 113–121.

Hallett, L.M.; Hsu, J.S.; Cleland, E.E.; Collins, S.L.; Dickson, T.L.; Farrer, E.C.; Gherardi, L.A.; Gross, K.L.; Hobbs, R.J.; Turnbull, L., and Suding, K.N., 2014. Biotic mechanisms of community stability shift along a precipitation gradient. *Ecology*, 95(6), 1693–1700.

Hao, Z. and AghaKouchak, A., 2013. Multivariate Standardized Drought Index: A parametric multi-index model. *Advances in Water Resources,* 57, 12–18.

Heim, R., Jr., 2002. A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society,* 83(8), 1149–1165.

Henderson, K.G. and Vega, A.J., 1996. Regional precipitation variability in the southern United States. *Physical Geography*, 17(2), 93–112.

Hilderbrand, R.H.; Watts, A.C., and Randle, A.M., 2005. The myths of restoration ecology. *Ecology and Society,* 10(1), Article 19.

Hupp, C.R., 2000. Hydrology, geomorphology and vegetation of Coastal Plain rivers in the south-eastern USA. *Hydrological Processes*, 14(16–17), 2991–3010.

Intergovernmental Panel on Climate Change (IPCC), 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the Intergovernmental Panel on Climate Change*. Cambridge, U.K.: Cambridge University Press, 582p.

Jentsch, A.; Kreyling, J., and Beierkuhnlein, C., 2007. A new generation of climate change experiments: Events, not trends. *Frontiers in Ecology and the Environment*, 5(7), 315–324.

Keetch, J.J. and Byram, G., 1968. *A drought index for forest fire control. Research Paper SE-38*. Asheville, North Carolina: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, 32p.

Knapp, A.K.; Carroll, C.J.W.; Denton, E.M.; La Pierre, K.J.; Collins, S.L., and Smith, M.D., 2015. Differential sensitivity to regional-scale drought in six central U.S. grasslands. *Oecologia,* 177(4), 949–957.

Lackstrom, K.; Haywood, B.; Brennan, A.; Davis, J., and Dow, K., 2014. Drought and coastal ecosystems: Identify impacts and opportunities to inform management. *Proceedings of the 2014 South Carolina Water Resources Conference* (Columbia, South Carolina), pp. 1–5.

Lake, P.S., 2003. Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology,* 48(7), 1161–1172.

Lake, P.S., 2011. *Drought and Aquatic Ecosystems: Effects and Responses*. Chichester, U.K.: Wiley, 400p.

Livada, I. and Assimakopoulos, V.D., 2007. Spatial and temporal analysis of drought in Greece using the Standardized Precipitation Index (SPI). *Theoretical and Applied Climatology,* 89(3–4), 143–153.

Ntale, H.K. and Gan, T.Y., 2003. Drought indices and their application to East Africa. *International Journal of Climatology*, 23(11), 1335–1357.

Palmer, W., 1965. *Meteorological drought*. *U.S. Weather Bureau Research Paper No. 45*, pp. II–58.

Perry, J.E. and Atkinson, R.B., 1997. Plant diversity along a salinity gradient of four marshes on the York and Pamunky Rivers in Virginia. *Castanea*, 62(2), 112–118.

Petes, L.; Howard, J.; Helmuth, B., and Fly, E., 2014. Science integration into U.S. climate and ocean policy. *Nature Climate Change,* 4(8), 671–677.

Quiring, S.M., 2009. Monitoring drought: An evaluation of meteorological drought indices. *Geography Compass,* 3(1), 64–88.

Ross, I.; Misson, L.; Rambal, S.; Arneth, A.; Scott, R.L.; Carrara, A.; Cescatti, A., and Genesio, L., 2012. How do variations in the temporal distribution of rainfall events affect ecosystem fluxes in seasonally water-limited Northern Hemisphere shrublands and forests? *Biogeosciences,* 9(3), 1007–1024.

Rozas, L.P. and Odum, W.E., 1987. Use of tidal freshwater marshes by fishes and macrofaunal crustaceans along a marsh stream-order gradient. *Estuaries*, 10(1), 36–43.

Seager, R.; Tzanova, A., and Nakamura, J., 2009. Drought in the southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change. *Journal of Climate,* 22(19), 5021–5045.

Shukla, S.; Steinemann, A., and Lettenmaier, D., 2011. Drought monitoring for Washington State: Indicators and applications. *Journal of Hydrometeorology,* 22(1), 66–83.

Tilman, D. and Downing, J.A., 1994. Biodiversity and stability in grasslands. *Nature,* 367, 363–365.

United States Geological Survey (USGS) Staff, 2002. *Chronology of major and other memorable floods and droughts in South Carolina, 1893–2002*. http://sc.water.usgs.gov/publications/pdf/SCFloodsandDroughts1893 2002.pdf.

van der Molen, M.K.; Dolman, A.J.; Ciais, P.; Eglin, T.; Gobron, N.; Law, B.E.; Meir, P.; Peters, W.; Phillips, O.L.; Reichstein, M.; Chen, T.; Dekker, S.C.; Doubková, M.; Friedl, M.A.; Jung, M.; van den Hurk, B.J.J.M.; de Jeu, R.A.M.; Ohta, T.; Rebel, K.T.; Plummer, S.; Seneviratne, S.I.; Sitch, S.; Teuling, A.J.; ven der Werf, G.R., and Wang, G., 2011. Drought and ecosystem carbon cycling. *Agricultural and Forest Meteorology,* 151(7), 765–773.

Vicente-Serrano, S.M.; Beguería, S., and López-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: The Standardized Precipitation Evapotranspiration Index. *Journal of Climate,* 23(7), 1696–1718.

Vicente-Serrano, S.M.; Beguería, S.; Lorenzo-Lacrus, J.; Camarero, J.J.; López-Moreno, J.I.; Azorin-Molina, C.; Revuelto, J.; Morán-Tejeda, E., and Sanchez-Lorenzo, A., 2012. Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interactions,* 16(10), 1–27.

Wilhite, D.A., (ed.), 2001: *Drought: A Global Assessment, Natural Hazards and Disasters Series 1*. London, U.K.: Routledge, 396p.