SCIENTIFIC INSTRUMENTS AND EARLY PLANT ECOLOGY IN THE U.S.A.

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Abstract

Scientific instruments occupied a significant place in research associated with early plant ecology in the U.S.A. around the turn of the 20th century. Frederic E. Clements' 1905 book, *Research Methods in Ecology*, allotted a leading role to instruments and instrumental methods while Burton E. Livingston enjoyed success when he devised a new instrument in 1906 that allowed him to pursue his research. This paper looks at the nature of these developments and how the status of scientific instruments then changed over time for these two ecologists.

> "The employment of instruments of precision is clearly indispensable for the task which we have set of ecology, and every student that intends to strike at the root of the subject, and to make lasting contributions to it, must familiarize himself with instrumental methods."
>
> From Frederic E. Clements, *Research Methods in Ecology* (1905).[1]

Introduction

In 1866, German zoologist Ernst Haeckel (1834-1919) coined the word 'Oecologie' with the idea of creating a gathering point for research that dealt with the relationship between living organisms and their environment. Ecology, as it became officially spelled following the 1893 International Botanical Congress held in Madison, Wisconsin, identified that field of science where knowledge from the diverse fields of biogeography, physiology, botany, zoology, and natural history could be considered and studied under a single banner.[2] In due course, ecology would mature to become a distinct scientific discipline as signaled by the founding of the British Ecological Society in 1913 and the Ecological Society of America in 1915.

It was during this time period from 1866 to 1915 that ecology, particularly plant ecology, began to utilize scientific instruments for research activities in the field and laboratory. Building on the work of Alexander von Humboldt who, earlier in the 19th century, used various scientific instruments to gauge environmental factors like air humidity and temperature, now microscopes and other tools were being employed to gather detailed information about plants as efforts grew to better understand the relationship between plants and environment in addition to describing concepts like plant communities and plant succession. As ecology developed during this time, first in Europe and then in the United States, so did a role for scientific instruments, and looking at this history should prove useful in gaining a richer understanding of the relationship between instruments and science.

By briefly discussing the European heritage of scientific instruments in biology and ecology, evidence showing the need and utility of scientific instruments will be established. Then, in moving to the United States, my paper looks at two American ecologists who made good use of scientific instruments in their research during this period of early plant ecology: Frederic E. Clements and Burton E. Livingston. Clements advocated that ecologists become familiar with instrumental methods and Livingston developed a new instrument for his own research. Both researchers required reliable data beyond what unaided senses could provide along with consistent measurements of factors found over increasingly larger geographical areas. Also, it will be shown that scientific instruments came into being solely for ecological research and this helps to support my view of ecology becoming a well-established science during this time.[3]

European Heritage of Scientific Instruments in Biology and Ecology

In the late 18th century, descriptive systems of plants that were merely taxonomic came to be seen as limited in providing the kind of information that explained geographic distribution of plants. For example, German plant geographer Alexander von Humboldt (1769-1859) employed scientific instruments to obtain the climatic and geographical data required for his biogeographic publications and maps. Specifically, his delineation of vegetation zones in South America was dependent on climatic and geographical values that only could be accurately and quantitatively determined with instruments. While humidity, elevation, temperature, and other environmental factors were measured by Humboldt, his field work during the early 19th century still remained largely descriptive and only showed what plant species lived in a certain environments, but not why those particular plants grew in a specific location.

Enlarging on Humboldt's work, the German Oscar Drude (1852-1933) conducted research in terms of ecological thinking when he deemed climatic conditions as having a determining effect on plant distribution. Drude continued to make measurements with instruments, but now he began to quantify the relative abundance of plant species by utilizing "categories ranging from 'social' (where a single species formed an overall mass) down to 'scarce.'"[4] In this way, Drude's research from the early 1890s, work later published in a 1896 book titled *Deutschlands Pflanzengeographie* (Plant Geography of Germany), followed the instrumental methods used by Humboldt and extended them to include measures that quantified plant abundance in addition to various environmental factors.

Appearing at the same time were two more European texts that proposed new concepts in ecology: *Oecological Plant Geography* by Eugenius Warming (1841-1924) of Denmark in 1895 and *Plant Geography on a Physiological Basis* in 1898 by Andreas W.F. Schimper (1856-1901) from the University of Bonn. Warming's book was considered a milestone in early ecological thought for introducing the concept of plant communities while Schimper studied physiological adaptations of plants to external conditions. A common background held by both Warming and Schimper was training and skill in using laboratory instruments, abilities then used for research in the field. Warming traveled "to Bonn to study microscopical technique"[5] and Schimper had a "laboratory background" via his "typically solid German training in experimental physiology."[6] Furthermore, Warming has been identified as being a rare naturalist who was an "enthusiastic and thoughtful field worker who was also comfortable and creative in the laboratory."[7]

In this way, scientific treatment of both biotic and abiotic dimensions became a single set of measurable factors for the dual locations of field and laboratory and now included data such as species population, light, soil, heat, and moisture information. Measurement data would guide Warming and Schimper in their thinking and helped to support their conclusions regarding plant distribution and physiological adaptations. Gathering data using scientific instruments for an expanding variety of environmental and plant factors would become more commonplace, if not mandatory, when developing ecological theories., This trend reached the United States prior to the turn of the 20th century as discussed next.

United States

Turning now to the United States, botanists like Asa Gray (1810-1888) of Harvard University carried out reserarch similar to what was being done in Europe. He carried out plant distribution studies in the mid-1800s while training a number of graduate students in this scientific field. One such student, Charles E. Bessey (1845-1915), implemented "significant changes" in the current American taxonomical traditions with the "introduction of laboratory instruction to the teaching of undergraduates" when he set up a new botanical laboratory at the Iowa Agricultural College in 1871.[8] Later during the 1880s, Bessey came to the University of Nebraska and brought with him "the first college microscopes to cross the Mississippi River."[9]

This friendly reception of an instrumental approach to botany would be inherited by one of his students, Frederic E. Clements, who would go on to become a professor at the University of Nebraska after graduating in 1898.[10] Along with the University of Chicago, this university would produce many students who, during the 1890s and 1900s, matured in parallel with the science of ecology and filled the slowly growing number of teaching positions in this field.[11] However, it would be Clements who became "the first philosopher of ecology" in the United States and contributed his intense personal energy to research in this promising science.[12]

Frederic. E. Clements

Frederic Edward Clements (1874-1945), an associate professor of plant physiology at the University of Nebraska, published in 1905 the first American book on ecology titled *Research Methods in Ecology*. Clements called this volume a "handbook" and his "account of the methods used by the author in his studies of the last eight years."[13] More than just methods, Clements was searching for a "broad and thorough system of ecological research" that could become the foundation for work in this field. Perhaps hinting at Clements' dogmatic tendencies that would appear in his later years, he wanted to discover "*a* guiding principle as will furnish *a* basis for *a* permanent and logical superstructure" for this system.[14]

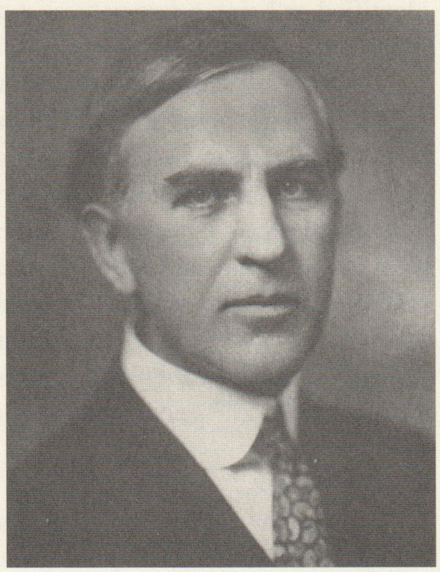


Fig. 1 Frederic Edward Clements

In ecological research, Clements' system gave highest priority to a single relation, this being the one between habitat and plant. He assigned the term 'cause' to habitat and 'effect' to plant with "plant as the primary effect of the habitat."[15] In addition, he designated a third term, 'formation,' to mean vegetation or "a sort of multiple organism." For each of these terms, habitat, plant, and formation, Clements defined those factors which could be measured and analyzed by instruments and his book provided details about various instruments, methods for instrument setup and use, and how to record and process data obtained via these instruments.

But knowledge of factors alone was not sufficient when considering a particular habitat as Clements wanted to know the specific quantity of each factor. "It is not sufficient to hazard a guess at this, or to make a rough estimate of it. Habitats differ in all degrees, and it is impossible to institute comparisons between them without an exact measure of each factor."[16] It would be necessary to appeal to instruments for determining the exact amount of a factor and this demand underlay his commitment to instrumental methods. This intense focus on exactness for habitats and factors extended to Clements' definition of vegetation which he regarded as "a complex organism with structures and with functions susceptible of exact methods of study."[17]

Clements divided factors of a habitat into two groups: physical and biotic. Physical factors, spilt into climatic and edaphic groupings, were "the real causative forces" and biotic factors had lesser influence. With priority given to physical factors, it is easy to understand why Clements' allocated a quarter of his book's pages to instruments and provided 16 definitions of various instruments in the book's glossary.[18] Some of these instruments listed by Clements included the geotome, soil borer, field balance, psychrometer, hygrometer, atmometer, compass, photometer, sun recorder, selagraph, barometer, clinometer, anemometer, thermometer, rain gauge, and the trechometer.

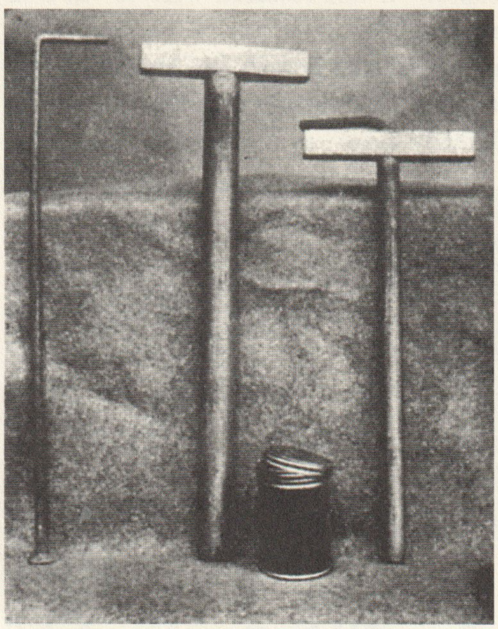
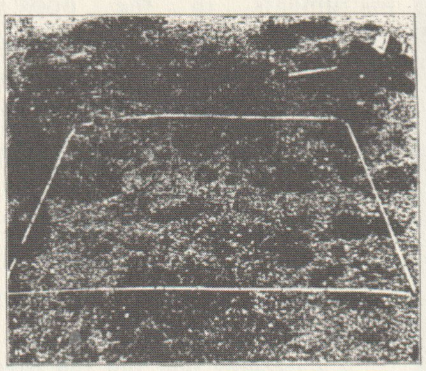


Fig. 2 Geotomes and a soil can.

Clements was not the first to utilize scientific instruments in his work as a number of these instruments had been used in prior research efforts such as Alexander von Humboldt's South America expedition where barometers, thermometers, and hygrometers were employed. What is critical to note here was the strength of Clements' call for instruments and instrumental methods, a call so strong that it set a tone that completely eliminated any thought of performing a mere descriptive taxonomy of plants. Coupled with the fact that these were simple instruments that were easy to setup and operate in the field, a key point when "a large number of instruments are in operation," Clements was ready and able to tackle sizeable geographical areas for his field studies.[19]

One instrument advocated by Clements was not a scientific instrument in the traditional sense, but was more of a simple field tool. The quadrat "is merely a square area of varying size marked off in a formation for the purpose of obtaining accurate information as to the number and grouping of plants present."[20] Developed by Clements in 1898 along with fellow University of Nebraska student Roscoe Pound (1874-1964), a quadrat was set up by simply using a long piece of string held at each corner with sticks and it typified a good example of instrumental methods that would support Clements' proposed system of precise ecological study. Descriptive research could continue as it was helpful for general field plant reconnaissance studies, but Clements felt that the quadrat "must be used for research work in the development and structure of vegetation" if this research were to "to bear fruit in the interpretation of the formation."[21]

Concern about accuracy was given particular priority in Clements' book. "It is better to have instruments that read too minutely than those which do not make distinctions that are sufficiently close" as it regarded instruments



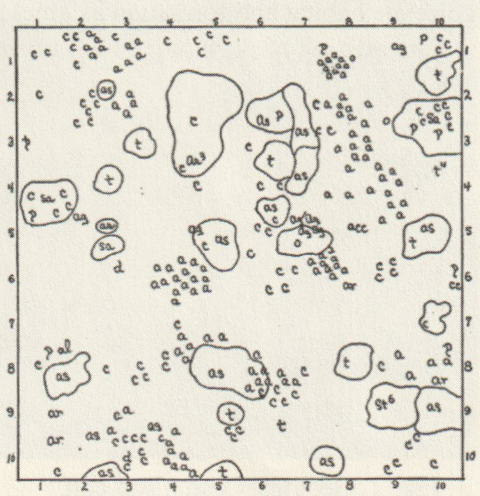


Fig. 3 A quadrat in the field (left) and chart produced from a quadrat (right).

measuring physical factors.[22] Linked to this desire for accuracy was the need for detecting 'efficient differences' which he defined as "the amount of a physical factor necessary to produce a change in the response" in a plant.[23] Inadequate knowledge regarding these efficient difference values for plant formations caused Clements to suggest using those species having a ready response to stimuli, a condition he termed plasticity. One worry about accuracy was raised when a normally accurate instrument was used to study a plant under abnormal conditions and thus producing inaccurate data, a problem that could be avoided if a plant was "studied while functioning normally in its own habitat."[24]

Clements' *Research Methods in Ecology* represented an important book because it described a new system for methods in ecology and explained in abundant detail the underlying concepts for this system. Interwoven with these methods were Clements' own views regarding ecological research: a focus on instrumental methods, his definitions and terminology, a demand for accuracy, and his idea of a fundamental relationship between habitat, plants, and formation. This very mechanical sounding system put forward cause and effect as its main theme where measure of responses, either in the field or the laboratory, formed the foundation of a potential theory. Not everyone agreed that this approach could be successful as complete enthusiasm for the book was not shared by Arthur G. Tansley (1871-1955) and Frederic F. Blackman (1866-1947) who reviewed it in late 1905. Ignoring Clements' application of instruments, they were concerned over his attempt to precisely measureplant factors in order to correlate this data with any functional or structural response from the plants, and said it would create "[p]remature anxiety to correlate habitat and formation as quickly and simply as possible" in regards to "the relation of plant and environment."[25]

Research Methods in Ecology may have been called a handbook by its author, but it was really Clements' ideas for developing ecological theory and time would tell if his views would survive in the hands of other ecologists. Tansley and Blackman did thank Clements for his book as it provided "great and lasting positive contributions to our subject."[26] Also, it may be seen as a hopeful beginning for a well defined and concentrated deployment of scientific instruments in ecological research, a question that will be further explored with a look at plant ecologist Burton E. Livingston.

Burton E. Livingston

Burton Edward Livingston (1875-1948) was a graduate student in the Botany department at the University of Chicago from 1899 to 1901. After publishing a paper in 1903 on "The Role of Diffusion and Osmotic Pressure in Plants,"[27] Livingston accepted a grant from the Carnegie Institution of Washington for research at their Desert Botanical Laboratory in Tucson, Arizona, for the summer of 1904.[28] This facility had only just been established in 1903 by botanist Frederic V. Coville (1867-1937) and plant physiologist Daniel T. MacDougal (1865-1958), scientists who had both knowledge of and experience with desert plants from earlier expeditions.[29] In 1906, Livingston produced an official report on his work titled "The Relation of Desert Plants to Soil Moisture and to Evaporation" and, during the course of this research, developed and utilized a form of atmometer, a scientific instrument employed for measuring evaporation.[30] Livingston's work with this instrument provides an excellent example of how scientific instruments proved themselves useful during this period of early plant ecology in addition to showing the necessity to develop an instrument

Fig. 4 Burton Edward Livingston (standing, third from the right).

specific to the needs of ecology.

Livingston wanted to better understand plant life in xerothermic conditions with "its centimeters of annual rainfall and its meters of annual evaporation."[31] His 1906 report first explored soil moisture questions and this was where a suggestion by Whitney and Cameron for an "artificial root hair" was followed in order to learn how soil held water against the osmotic pressure of a sugar solution.[32] This artificial root hair worked as a form of ordinary osmometer and Livingston specially designed his version of this instrument as an unglazed porcelain hollow cylinder 12.5 cm in length, 2.0 cm internal diameter, 3 mm in thickness, and closed at one end. Placed in the ground, the amount of solution in the cylinder was measured for flow into or from the soil, giving a result that offered "a very valuable means for quantitative studies of the mechanics of root absorption."[33]

Moving next to atmospheric studies, Livingston wanted to examine evaporation in a manner that would be sensitive to variations in air currents and capable of giving readings minute to minute. Existing instruments, some form of pan or vessel open to the air, determined this by measuring loss of water by weight or volume, but lacked the needed sensitivity desired by Livingston. An answer to this problem was discovered at hand, for as Livingston put it: "Happily, a method was hit upon, which, while it gives practically perfect results, is exceedingly easy of operation and requires a minimum of time and care."[34] His solution was to use the porcelain cylinder employed earlier for soil studies, now placed pointing upwards in the air connected to a water reservoir and using a graduated glass burette for measuring water level changes over time. One disadvantage of this design was that each instrument had unique characteristics and, therefore, had to be calibrated so values obtained from multiple instruments could be accurately compared.

Livingston was quite taken by his design, this new form of atmometer, and continued to improve it over the next ten years. In 1908, he wrote a short article for the journal *Science* that provided the essential details about the construction, arrangement, and deployment of a simple version that Livingston said was "very satisfactory" for the determination of the evaporating power of the air.[35] Next, a series of articles in the journal *The Plant World* from 1910 to 1915 communicated variations and improvements of his atmometer designs in addition to presenting the results gained from use of the instrument.[36] Plant physiologist John W. Shive (b. 1877) of Johns Hopkins University enhanced Livingston's design by creating a

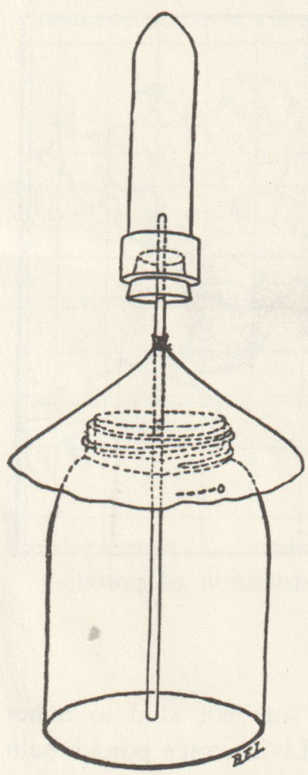


Fig. 5 The Simple Porous Cup Atmometer

version that was self-contained and less likely to break.[37]

Livingston's instrument for measuring evaporation proved itself useful for ecological studies and he could now claim that "by means of a new method involving a newly devised evaporimeter, a physiological regulation of the rate of transpiration was unquestionably shown to exist in the forms studied."[38] In his 1915 paper, Shive commented that "a large number of these instruments have come into use" and Livingston's co-researcher at the Desert Botanical Laboratory, Forrest Shreve, reported in 1911 that "a new series of atmometers was installed" which provided good results for his work in the Santa Catalina Mountains in southeastern Arizona.[39] Providing full details on using the atmometer, Livingston's articles detailed "all essential points as far as they have been worked out" in order to assist "the worker" so that he may give proper attention to porous cup atmometry "without [having] years of experimental acquaintance with the subject."[40] Indeed, this instrument was now stabilized to the point where it could be given to a trained worker in the field, a sign that this instrument had become part of a standard toolkit being utilized by plant ecologists in their research work.[41]

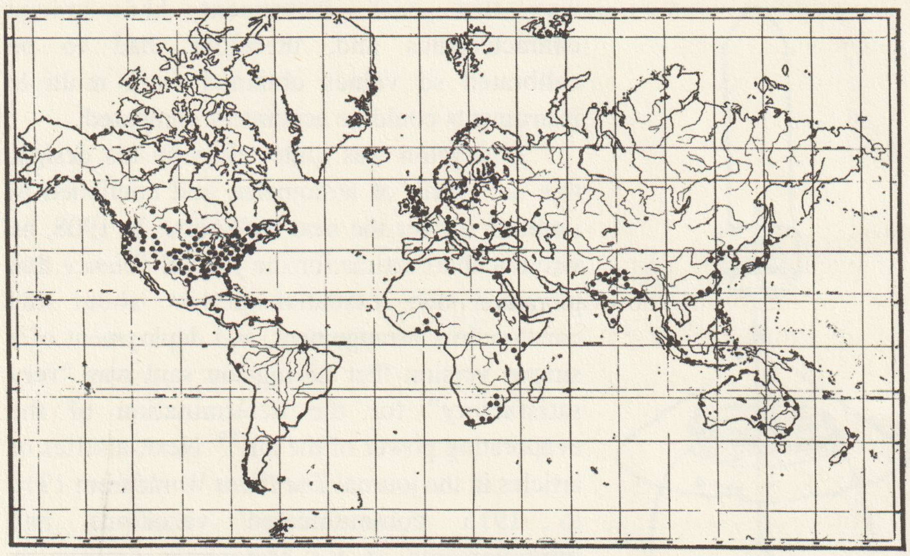


Fig. 6 World chart showing geographic distribution of porous-porcelain atmometers in the years 1925-1935.

Epilog

Beyond this period of early ecology, time was not kind to either Clements' push for instrumental methods or for Livingston's porous bulb atmometer as both saw diminished priority in the field of ecology for different reasons. It was not so much that instruments failed to support these ecologists in their research, but that instruments were insufficient by themselves to be a main component of any ecological theories or principles and, thus, became secondary as data gathering tools.

For Clements, his approach based on instrumental methods was not sufficient to gain an understanding of Nature because data provided by instruments could not be reconstructed into a system that would match the functioning of Nature under view. Instruments could be a part of his permanent and logical superstructure, but not by themselves be capable of giving any direct ecological explanations. In 1935, Clements himself confirmed this point by stating "instruments, though indispensable, must be relegated to a secondary position."[42] He had shifted away from instruments to employ instead the plants themselves and identified this new instrument by the term 'indicator.' "Every plant is an indicator" such that "each plant is the product of the conditions under which it grows, and is thereby a measure of these conditions."[43] This was the time when Clements proposed new theories on plant succession and climax formations where indicators would play a more important role than instruments. Instruments would be useful in "attempting a complete or partial analysis of the habitat" in that it "furnishes data for succession, but much of it is difficult of application or interpretation."[44] Thus, instrumental methods and exact measurements gave way to plant indicators because indicators now had a stronger affinity with Clements' revised ecological views.

For Livingston, his clay bulb atmometer lost favor over time to the simplicity of the open pan, an undemanding instrument used as the standard tool for measuring the evaporative power of the atmosphere by the U.S. Weather Bureau.[45] A 1947 ecology text listed both the open pan and porous clay bulb atmometer devices and specifically referred to the atmometer as being "widely used by ecologists" and indicated that "the sole manufacturer and distributor of spherical pottery atmometers" was Livingston himself.[46] By 1989, however, a book on field methods and instrumentation for plant physiology studies makes no mentions of the atmometer and only the open pan and Piche evaporimeter were described.[47] Both texts gave references for government publications regarding the open pan and this suggests that a standardized and simpler device held a greater appeal for ecological research than an instrument "nearly similar to the corresponding features of plants in general."[48] While measuring atmospheric evaporation in plant ecology studies remained important from this period of early ecology to the present time, it seems clear that the design of apparatus used this research work would change based on factors guided by practical needs and government standards rather than the physiological mimicry of the plants themselves.

Conclusions

Albert Van Helden defines a scientific instrument to "mean a device used by scientists to investigate nature qualitatively or quantitatively" under an assumption "there is a proper, even essential, place for such devices in the study of nature since the human senses alone are too limited for most scientific investigations."[49] During this period of early ecology, Clements placed great hope in instrumental methods as they would better the human senses for exact observations and data gathering that would support his ecological ideas and methods. Similarly, Livingston embraced instruments and worked for more than a decade in developing one specific to his own investigations. But were scientific instruments truly helpful and were they "clearly indispensable" as Clements claimed in his 1905 book?[50]

Did instruments lead Clements astray when he gave them so much emphasis in his book? Perhaps when he found that all this instrumental data was too indirect for him to recover a useful working view of plant ecology and, as a result, this failure caused him to reconsider and select a better source for obtaining data, this being plant indicators.[51] With instruments, there were too many factors to measure one by one where plants by themselves could integrate these factors and return a more direct and efficient measurement. Possibly for Clements, using instruments caused the dynamics of ecology to be lost in exchange for a huge pile of data readings, and, as a result, he found the idea of plant indicators to be more in concert with plant ecology as he viewed it. While instruments may have failed to support Clements ideas for plant ecology initially, they, in effect, guided him to the instruments that could, these being the plants themselves.

An instrument, the porous bulb atmometer, helped Livingston enjoy respectable success with his field research. He embraced the notion that instruments could provide useful data that would facilitate his further understanding of desert plant ecology. Furthermore, he avoided any sense of holding up instruments for their own sake and, in this regard, he criticized Clements and his "*awful* book" saying it had "nothing to it" because of the verbiage allotted to methods and instruments.[52] However practical this instrument was for him and others, it was destined to be replaced by a simpler device, the open pan, which was becoming a standard instrument for large government agencies. It was likely that the absence of any standard units for atmometer measurements forced this selection, that, in contrast, an open pan evaporimeter and a rain gauge did share measurement units for the height or weight of water lost or gained respectively. This would become a critical issue for groups of researchers analyzing data from these two types of instruments scattered over a large geographical area and managed by many different individuals who would be trying to reach consensus over their observations. The unique characteristics of each Livingston atmometer would make any data comparisons difficult and its design and fragile parts would make it less desirable compared to a simple metal pan. And more significant, with Livingston being the primary source for these porcelain clay bulbs, when he died in 1948, this effectively signaled an end for his instrument in ecological research.[53]

For Clements and Livingston, scientific instruments occupied a significant place in their research work during this period of ecology in the early 1900's. Clements' 1905 book, *Research Methods in Ecology*, delegated a essential role to instruments and instrumental methods while Livingston had good success in devising a new instrument in 1906 that allowed him to perform his ecology research. While instruments may have faded in terms of importance and popularity during this early period of plant ecology, it remains clear that scientific instruments did have a place in early plant ecological research and played an essential role in the development of this science.

Acknowledgement: I wish to thank Jane Camerini for her encouragement and support in my writing this paper.

Table of Scientific Instruments referenced by Frederic E. Clements in his book *Research Method in Ecology*[54]

Instrument	**Definition**
anemometer	an instrument for measuring wind velocity.
atmometer	an instrument for measuring evaporation.
barometer	an instrument measuring atmospheric pressure and for finding elevation.
clinometer	an instrument measuring the slope of a surface.
compass	an instrument that indicates geographic direction via a magnetic needle.
field balance	a portable instrument taken to the field for weighing soil samples, etc.
geotome	an instrument for obtaining soil samples.

hygrometer	an instrument designed to measure humidity.
photometer	an instrument for measuring light intensity using a photographic method.
psychrometer	an instrument that measures humidity by means of a fall in temperature.
rain gauge	an instrument for measuring the amount of rain.
selagraph	an instrument for recording light values automatically.
soil borer	an instrument for obtaining soil samples at depths of two to eight feet.
sun recorder	an instrument following the movement of the sun recording light intensity.
thermometer	an instrument measuring the temperature of air, soil, etc.
trechometer	an instrument for measuring run-off.

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Notes

1. Frederic Edward Clements, *Research Methods in Ecology* (Lincoln, Nebraska: University Publishing Company, 1905), p. 20.

2. Donald Worster, *Nature's Economy: A History of Ecological Ideas*, 2nd ed. (Cambridge: Cambridge University Press, 1994), p. 192.

3. My focus on instruments sidesteps questions involving the siting of these instruments and whether they are being used in what one would properly call a field or laboratory setting. Nonetheless, both Clements and Livingston can be seen as gaining legitimacy for their research through the use of instruments and this provides sufficient grounds for exploring their history in this paper.

4. Peter J. Bowler, *The Fontana History of the Environmental Sciences*, (London: Fontana Press, 1992), p. 370.

5. William Coleman, "Evolution into Ecology? The Strategy of Warming's Ecological Plant Geography," *Journal of the History of Biology*, **19,** No. 2 (Summer 1986), 181-196, p. 185.

6. Op cit., ref. 2, p. 198.

7. Op cit., ref. 5, p. 185.

8. Eugene Cittadino, "Ecology and the Professionalization of Botany in America, 1890-1905," in William R. Coleman and Camille Limoges (eds.),

Studies in History of Biology, Vol. 4 (Baltimore: Johns Hopkins University Press, 1977), p. 175.

9. Op cit., ref. 2, p. 208.

10. Ronald C. Tobey, *Saving The Prairies: The Life Cycle of the Founding School of American Plant Ecology, 1895-1955,* (Berkeley: University of California Press, 1981), pp. 76-79.

11. Ibid, pp. 122-127.

12. Ibid, p. 76.

13. Op cit., ref. 1, Preface.

14. Ibid, p. 16. My italics.

15. Ibid, p. 17.

16. Ibid, p. 20.

17. Ibid, p. 5.

18. Out of the 334 pages in Clements, pages 24-87 comprise the section "Construction and Use of Instruments" while other instrument references, specifically his discussion of the quadrat, can be found in the "Methods of Investigation and Record" section of his book. See the table at the end of this paper for the instruments listed in the book's glossary.

19. Ibid, p. 24.

20. Ibid, p. 162.

21. Ibid, p. 161.

22. Ibid, p. 24.

23. Ibid, p. 317.

24. Ibid, p. 104.

25. F. F. Blackman, and A.G. Tansley, "Ecology in Its Physiological and Phyto-Topographical Aspects," *The New Phytologist,* **4** (No. 9), (November 29th, 1905), 199-203, 232-253. See p. 253.

26. Ibid.

27. Burton E. Livingston., *The Role of Diffusion and Osmotic Pressure in Plants*, (Chicago: University of Chicago Press, 1903), 2nd series, Vol. 8.

28. William G. McGinnies, *Discovering the Desert: Legacy of the Carnegie Desert Botanical Laboratory*, (Tucson, Arizona: The University of Arizona Press, 1981), p. 5.

29. Op cit., ref. 8, p. 183.

30. Burton Edward Livingston, *The Relation of Desert Plants to Soil Moisture and to Evaporation* (Washington, D.C.: Carnegie Institution, 1906), Publication No. 50.

31. Op.cit., ref. 27, p. 5.

32. M. Whitney, and F.K. Cameron, *The Chemistry of the Soil as Related*

to Crop Production, (Washington, D.C.: U.S. Gov. Printing Office, 1903), U.S. Department of Agriculture, Bureau of Soils, Bulletin 22, p. 54.

33. Op. cit., ref. 30, p. 22.

34. Ibid, p. 25.

35. Burton Edward Livingston, "A Simple Atmometer," *Science*, **28** (September 4, 1908), 319-320. See p. 319.

36. Burton Edward Livingston, "A Rain-Correcting Atmometer for Ecological Instrumentation", *The Plant World*, **13** (April, 1910), 79-82; Burton Edward Livingston, "Operation of the Porous Cup Atmomete", *The Plant World*, **13** (May, 1910), 111-119; Burton Edward Livingston, "A Study of the Relation between Summer Evaporation Intensity and Centers of Plant Distributions in the United States", *The Plant World,* **14** (Sept., 1911), 205-222; Burton Edward Livingston, "Paper Atmometers for Studies in Evaporation and Plant Transpiration", *The Plant World,* **14** (Dec., 1911), 281-289.

37. John W. Shive, "An Improved Non-Absorbing Porous Cup Atmometer", *The Plant World*, **18** (1915), 7-10.

38. Op. cit., ref. 30, p. 76.

39. Op. cit., ref. 37, p. 7; Forrest Shreve, *The Vegetation of a Desert Mountain Range as Conditioned by Climatic Factors,* (Washington, D.C.: Carnegie Institution, 1915), Publication No. 217, p. 63.

40. Burton Edward Livingston, "Atmometry and the Porous Cup Atmometer - Part I", *The Plant World*, **18** (No. 2), 21-30, 1915; Part II," *The Plant World*, **18** (No. 3), 51-74, 1915; Part III, *The Plant World,* **18** (No. 4), 95-111, 1915; Part IV, *The Plant World*, **18** (No. 5), 143-149, 1915. Quotes from page 21 of Part I.

41. Burton Edward Livingston, "Atmometers of Porous Porcelain and Paper, Their Use in Physiological Ecology", *Ecology*, **16** (July, 1935), 438-472. This journal article is Livingston's summing up of atmometry and shows how his porous bulb atmometer enjoyed world-wide distribution and use (see his map on page 443 reproduced here as Fig. 6).

42. B.W. Allred and Edith Gertrude Clements, *Dynamics of Vegetation; Selections from the Writings of Frederic E. Clements,* (New York.: H.W. Wilson Co., 1949), p. 251. This is a reprint of an earlier journal article by Frederic E. Clements, "Experimental Ecology in the Public Service," *Ecology,* **16** (July 1935), 342-363, p. 347.

43. Frederic E. Clement, *Plant Indicators: The Relation of Plant Communities to Process and Practice,* (Washington, D.C.: Carnegie Institution, 1920), Pub. No. 290, p. 28. This concept also appear in Frederic

E. Clements and Glenn W. Goldsmith, *The Phytometer Method in Ecology: The Plant and Community as Instruments,* (Washington, D.C.: Carnegie Institution, 1924), Pub. No. 356.

44. Frederic E. Clements., *Plant Succession and Indicators; a Definitive Edition of Plant Succession and Plant Indicators,* (New York: H.W. Wilson Co., 1928), p. 200.

45. Benjamin Clinton Kadel, *Measurement of Precipitation. Instructions for the Measurement and Registration of Precipitation by Means of the Standard Instruments of the United States Weather Bureau,* (Washington, D.C.: U.S. Govt. Printing Office, 1936), U.S.D.A., Weather bureau. Circular E. 4th edition.

46. R.F. Daubenmire, *Plants and Environment, a Textbook of Plant Autecology* (New York: John Wiley & Sons Inc., 1947), pp. 95-96.

47. R.W. Pearcy, J.R. Ehleringer, H.A. Mooney and P.W. Rundel, *Plant Physiological Ecology: Field Methods and Instrumentation,* (London ; New York: Chapman and Hall, 1989), p. 50. Further confirmation of this trend towards other instruments can be found in the third edition of Daubenmire's book published in 1974 which added the Piche evaporimeter to its list of instruments used for measuring the evaporative power of the air. See R.F. Daubenmire, *Plants and Environment, a Textbook of Plant Autecology*, 3rd ed. (New York: John Wiley & Sons Inc., 1974), p. 84.

48. Op. cit., ref. 40, Livingston, Part III," p. 110.

49. Albert van Helden, "The Birth of the Modern Scientific Instrument", in John Burke (ed.), *The Uses of Science in the Age of Newton*, (Berkeley: University of California Press, 1983), p. 49.

50. Op. cit., ref. 1, p. 20.

51. Op. cit., ref. 43.

52. Letter from B.E. Livingston to D.T. MacDougal, 26 Jan. 1918, Arizona Heritage Center, Arizona Historical Society, in Janice Emily Bowers, *A Sense of Place: The Life and Work of Forrest Shreve,* (Tucson, Arizona: The University of Arizona Press, 1988), p. 59.

53. A curious footnote to this outcome comes from the fact that Livingston never mentioned a source for these clay bulb atmometers in any of his papers and this suggests that these bulbs were easily obtained as common scientific supply items. I was unable to obtain any laboratory supply catalogs from this period to check further on this point.

54. Op. cit., ref. 1, pp. 314-323. These pages are the glossary section of his book and included these 16 instrument definitions.

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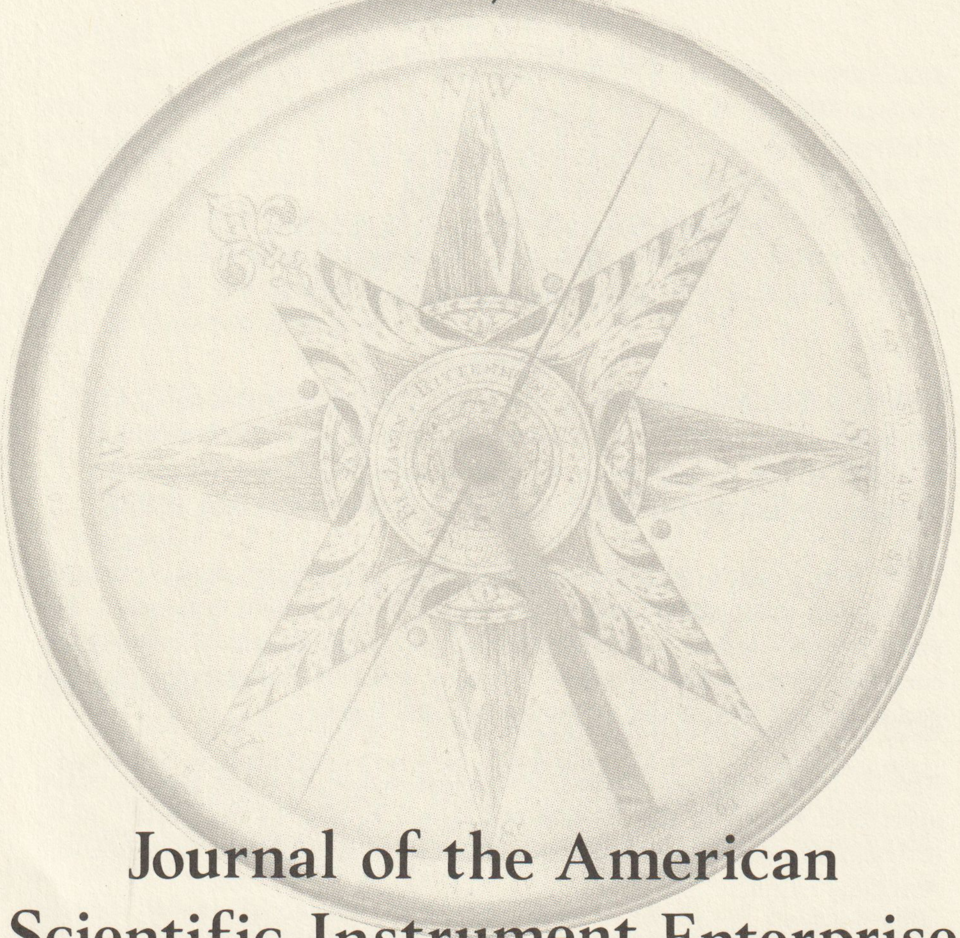

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