Professor Pierre Legendre
Full professor, Département de sciences biologiques,
Université de Montréal
Canada

Université de Montréal

CABINET DU RECTEUR

Montreal, 16 February 2023

World Cultural Council
Case Postale 373
1630 Bulle 2
Switzerland

Subject: Nomination of Professor Pierre Legendre for the *Albert Einstein World Award of Science*

Distinguished members of the Selection Committee,

Considering his immense contribution to the development of *Numerical Ecology* as a new, dynamic branch of ecology, his teaching around the world and his deep impact on the international research community, it is my privilege to nominate Professor Pierre Legendre for the Albert Einstein World Award of Science.

Importance of his scientific achievements

With the advent of computers in the 1950's, ecology, which was previously mostly descriptive, evolved to become a hypothesis-testing science. The use of quantitative data to test hypotheses grew with the availability of methods of data analysis. Statisticians and methodologists in application fields had been at work since the beginning of the 20th century, developing general-purpose methods of data analysis. It is in this dynamic context that *Numerical ecology* emerged, with ecologists developing specific methods of analysis to address ecological questions; they did that by integrating specific elements of ecological theory, like niche, indicator species, and beta diversity theories, into the methods of analysis. Under the lead of Pierre Legendre, a new generation of mathematically-trained ecologists was mobilized to develop the new research field. A network of contributors to Numerical ecology is shown in an encyclopaedia article by Pierre Legendre (2019) describing the development of Numerical Ecology[1]. This network shows that the development of numerical ecology has been the result of a broad and fruitful collaboration among many scientists.

> *Numerical Ecology* is the field of quantitative ecology devoted to the numerical analysis of multivariate community data, aimed at understanding the processes that generate and maintain biodiversity in ecosystems. Community ecologists are among the primary users of these methods.

In quantitative ecology and ecological statistics, Pierre Legendre is by far the most highly cited. Among the leading ecologists worldwide, he is ranked fifth by Google Scholar for the number of citations by his peers[2]. In the field of Environment/Ecology, he is the only scientist worldwide, all environmental disciplines included, who is *Web of Science Highly Cited Researchers* in all lists published during 21 years, firstly in 2001, then every year from 2014 to 2021.

[1] http://www.numericalecology.com/Reprints/Legendre_Numerical_Ecology_EoE2_2019.pdf
[2] https://scholar.google.com/citations?view_op=search_authors&hl+en&mauthors=label:ecology

His innovative work has revolutionized the way ecologists extract information from data to answer pressing questions about the preservation of biodiversity and the future of ecosystems. As the founder of the field of Numerical Ecology, he has contributed extensively to its development in the primary scientific literature over the past 45 years, with over 300 peer-reviewed papers, 13 textbooks and 22 book chapters. His 10 most important scientific contributions to this field are shown in an appended document.

His research papers have been cited more than 49,000 times according to Clarivate Web of Science and, adding his books and software, more than 135,000 times according to Google Scholar. During his highly productive career, he has combined ecology and mathematics, inventing, describing, programming and teaching new statistical methods designed to address urgent ecological problems, at home and around the world. These methods allowed ecology to make important progress in the computer age.

The statistical ecology work of Pierre Legendre is grounded in his fundamental contributions to ecology. He was among the first ecologists (with Simon Levin, another Google Scholar highly cited researcher in ecology) to develop the paradigm of the importance of spatial structures for ecological theory; this key message from one of his highly cited papers (1993, cited 4,400 times) has revolutionized the way ecologists now approach ecosystems. Prior to that, spatial relationships among observations in ecosystems were mostly considered to be statistical nuisances. In this paper, Legendre explained that these spatial structures are a fundamental property of ecosystems, one that creates the conditions for their functioning as ecological and thermodynamic machines. This idea is now widely accepted among researchers. After nine more years of research, he and ecologist Daniel Borcard developed a new approach, called Moran's Eigenvector Maps, which allows ecologists to dissect ecological patterns among spatial scales in order to identify the processes acting at these different scales; this new approach used another type of analysis, variation partitioning, which had been developed and published by the two colleagues in 1992. The paper describing Moran's Eigenvector Maps analysis, published in 2002, is also one of Legendre's highly cited papers. This shows that the new concept and method are largely accepted and used today by ecologists. In 2014, he extended this method of analysis to temporal processes and spatio-temporal analysis. Studying how ecosystems are organized in space and the conditions that allow them to function through time are especially important for decision makers who are now discussing how to slow or reverse the degradation of ecosystems that has taken place during the recent Anthropocene.

Legendre is a very active researcher. During the last six years (2017–2022), he published 45 refereed papers and book chapters, eight of them as first or single author; the other papers were written with graduate students, postdoctoral researchers and colleagues. His students and himself spoke at 27 national and international conferences and presented 14 research seminars on invitation in universities and scientific institutes.

A long, creative quest

Early in his career, Pierre Legendre undertook to synthesize the information available in the scientific literature about the statistical analysis of ecological community and ecosystem data; these data are multivariate by nature (i.e., they contain many variables, including the hundreds or thousands of species forming ecological communities). He had been trained in this type of analysis during his Ph.D., obtained in 1971 at the age of 24, during which he studied and contributed to the development a new research field, numerical taxonomy. He carried out that synthesis work with his brother, the oceanographer Louis Legendre. They set the bases for a new branch of ecology, which they called *Numerical Ecology*, in a book first published in French by *Masson* (Paris) in 1979. Then the brothers prepared a first English edition published by *Elsevier Science* (Amsterdam) in 1983. It was followed by a second French edition in 1984, then a second and a third English editions in 1998 and 2012.

The development of statistical methods is an intrinsic part of Legendre's research on ecological processes, where he iterates between testing ecological hypotheses and devising statistical models. Besides his new methods, he has published with his graduate students, postdoctoral researchers and other collaborators a wide variety of applications of numerical

approaches to the analysis of real ecosystems, sometimes exotic, located in different parts of the world, like Pacific atolls, hydrothermal vents in the sea abyss, and tropical forests in China and other countries.

Computation methods have radically changed during the past decades. From 1972 to 2004, Legendre and researchers in his lab wrote and distributed, for free, programs written in the Fortran and Pascal computer languages, promoting the *Open Source* approach to science well before it was officially defined (http://opensource.org/definition). In 2004, they moved to the *R Statistical Language*, developed for statistical analysis, to which scientists around the world are contributing; it is freely available for all computer platforms and operating systems, in particular MS Windows, Mac OSX and Linux. On that same year (2004), Legendre started teaching undergraduate and graduate students how to use R. He then translated most of his lab's previous Fortran and Pascal software to the R language, and that software is now distributed in major R packages, including *vegan*, *ade4* and *ape*, as well as a new package for spatial and temporal analysis of ecological data, *adespatial*, which was released on the CRAN site in May 2016. The most recent developments are made available on the Legendre lab Web page (numericalecology.com).

As he was working on the 3rd English edition of *Numerical Ecology*, Pierre Legendre asked his colleague Daniel Borcard to take the lead in the preparation of a book that would describe how to compute the different statistical analyses discussed in the then upcoming edition (called "the green book" by students because of its cover) using R software. In 2011, Borcard published the new "orange book", *Numerical Ecology with R*, with François Gillet (Université de Besançon, France) and Pierre Legendre as co-authors[3]. The stage was set for launching the 3rd English edition of *Numerical Ecology*, which appeared in 2012. The science reported in Legendre's "green book" is first-hand, based to a great extent on his own methodological research and his field experience in community ecology.

Impact of his work

The *Numerical Ecology* handbook is the most widely used book on the subject in the world. Its success is attested to by its citation rate: over 25,000 citations across all editions and languages. Graduate students and researchers around the world study the statistical methods in this book and write to Pierre Legendre for advice on study designs or the most appropriate procedures for the analysis of their data. Legendre receives dozens of messages on this topic every week. Acting as a one-person centre for consultation on numerical ecology, he answers personally, providing advice, warnings, computer functions and references.

Instead of enumerating all research fronts to which Legendre has contributed, I will particularly outline one example where his contributions have changed the way researchers study ecosystems.

The role of space — Ecologists have long been interested in using spatial data about their sampling units in ecosystems to model the spatial organization of multispecies communities. However, the similarity of communities that are close to one another in space produces spatial autocorrelation in the data, a phenomenon which invalidates the tests of significance of the relationships between community structure and environmental variables. The spatial dependence of observations, which is so prevalent in nature, means that the conclusions drawn from statistical tests are invalid in many cases in ecology and geography. Pierre Legendre was among the first ecologists to recognize this problem and propose solutions. In the late 1980's and early 1990's, he published a series of fundamental papers on spatial correlation, the detection of spatial patterns in ecosystems, and the analysis of heterogeneous phenomena in space, either as single author or with his graduate and postdoctoral students. Ecologists are still referring to these papers with respect to how to conduct surveys through

[3] A 2nd English edition of the R book was published by Springer in March 2018. Two Chinese editions were published by Higher Education Press, Beijing, in 2014 and 2020. An edition in Japanese will be published in Tokyo by Kyoritsu Shuppan Co. Ltd on 28 February 2023.

space. Ways of handling and controlling for spatial dependence in statistical tests are described in “the green book” and are now available to all researchers.

A key paper in that series, published in 1993 in the leading journal *Ecology*, is entitled “Spatial auto-correlation: Trouble or new paradigm”. It is considered a classic in ecology, with more than 4,400 citations. A series of papers followed in the 2000s, developing the analysis of multi-species data matrices sampled through space. One of these papers presented a major discovery: with his colleague Borcard, Legendre showed how it was possible to model community composition data at multiple spatial scales, distinguishing the signature of driving phenomena at (for example) broad, intermediate and fine scales, and relating the variation at specific scales to particular environmental processes. A few years later, he extended that method to the analysis of phenomena that are caused by directional physical processes, like the dispersion of plankton by oceanic currents (paper 3.182 in CV). It was then extended further to the analysis of temporal and spatio-temporal community composition data (paper 3.259).

In parallel to the development of multi-scale modelling, Legendre devoted a great deal of his research effort of the past few years to the ecological processes that generate and maintain the spatial differentiation of ecological communities among sites, called *beta diversity*, in ecosystems. This is an important property, targeted presently by ecosystem protection and management measures. This line of research has led to a series of works by which he first showed that beta diversity can be correctly estimated by the variance of the community composition data (paper 3.161) and that this beta index can be decomposed into Local Contributions to Beta Diversity (LCBD) and Species Contributions to Beta Diversity (SCBD; paper 3.254). He then developed the idea of statistically comparing successive surveys of a set of sites. Such repeated surveys are routinely conducted by various research organizations, like the forest dynamics plots associated with the Forest Global Earth Observatory (ForestGEO), and in government departments devoted to nature conservation. He has also shown (paper 3.204) how space-time interaction can be tested for significance in these data, in the absence of replication, and how a significant space-time interaction indicates that the spatial structure has changed among surveys, this being the signature of a climatic, anthropogenic, or other broad-scale change in the communities of the survey area.

The most recent development focuses on temporal beta diversity. The basic question is: in what ways do the observations at individual sites differ between surveys conducted at time 1 (T1) and time 2 (T2)? In particular, are there sites with exceptional changes in community composition between T1 and T2? And what do these changes consist of? Legendre worked with researchers and graduate students from labs in different countries who were posing these types of questions, developing a statistically valid way to answer them. Four application papers from four different ecosystems and parts of the world appeared in high-level ecology journals (papers 3.274, 3.289, 3.294 and 3.308). The manuscript fully describing the method was published in March 2019, immediately followed by a paper presenting an elaborate application of the new method to the well-known Barro Colorado Island Forest Dynamics plot in Panama (papers 3.304 and 3.305).

A surprising diversity of applications — Pierre Legendre has not only advanced knowledge in ecology, his field of expertise. He has also provided essential keys to researchers in related disciplines, from geography and earth sciences to oceanography. In each of these disciplines, he introduced new concepts and proposed novel perspectives on nature. For instance, with colleagues in the social sciences, he published spatial analyses of sociological and criminological data. One of his surprising contributions was a study (3.73 in CV) that used tasting data on single malt Scotch whiskies to illustrate the generality of application of some methods of comparison of data sets used by ecologists and practitioners working in other disciplines. In 2004, he used the whisky data again to illustrate a new method of concordance analysis of several data sets, which he published in a statistical journal (paper #3.153). He then immediately published, in an ecological journal, an application based on this method to identify species associations in ecosystems (paper #3.160, 2005).

Research and teaching going hand in hand

Pierre Legendre has taught quantitative methods to large classes of undergraduate students at Université de Montréal for 25 years. He has also taught methods of multivariate analysis to graduate students, a course that he is still offering once a year. He received the *Excellence in Teaching Award* from from his university and a similar one from his faculty (Arts and Science). For him, teaching and research are intertwined activities in the lives of university-based researchers. Research satisfies the curiosity of scientists, while teaching provides opportunities to explain the results of research to the next generation. It forces professors to dig into their knowledge in order to fully understand what they are teaching, which is a condition for delivering clear explanations of complex subjects; it also leads, in return, to better research. In his teaching of biological statistics to undergraduates, and of numerical ecology to graduate students, Legendre has always used the research-teaching cross-fertilization. This enabled him to publish the great books that students and researchers read and refer to.

As his papers and first books became known, Legendre started receiving invitations to develop short courses of 1 to 5 days on numerical ecology, firstly in France, Italy, Belgium, Spain, Norway and the USA. From 1990 to 2000, he was part of a team of three specialists who taught introductory classification methods to new participants, before the annual meetings of the Classification Society of America. He kept accepting invitations and altogether he has now given 86 such short courses at 56 universities and scientific research institutes in 19 countries across the globe. This is another measure of his recognition as a numerical ecologist and a teacher. As an example, during the summer of 2021, he gave a new advanced short course on time series analysis, on-line, to 60 scientists from 23 countries around the Atlantic Oceans, North and South, who were participating in the iAtlantic international research effort.

Legendre derives intellectual profit from these short courses: they provide opportunities discuss with colleagues and graduate students around the world about their research, to build international collaborations, discover new ecological data and questions, and elaborate new statistical methods to answer these questions. Fundamentally, he strongly believes that young researchers — the future of ecology — ought to receive the best possible training, including in developing countries.

Inspiration for future generations

At all university levels, Pierre Legendre is an outstanding teacher. He is enthusiastic, rigorous and open, and he expresses his passion for good science. He has a talent for explaining complex statistical methods in a clear way and making them understandable to students. In return, he encourages students to attain high levels of achievement during their academic formation. At the graduate level, he has supervised 22 M.Sc. and 16 Ph.D. students as well as 27 postdoctoral researchers, in addition to the great many researchers who visit his lab for weeks or months each year to learn from him. Of these students and postdoctoral fellows, many are pursuing brilliant careers as academics or researchers in Canada and abroad. As described in the previous section of this letter, he has been called upon to give advanced courses of numerical ecology in many countries. This is a genuine measure of his international standing.

One of the most striking things for visitors is the dynamism and creative climate prevailing in his lab. This research cauldron reflects Legendre’s method for generating discoveries: ideas pop up and are discussed to generate new ways of looking at nature and unveil its secrets. Pierre Legendre is literally at the centre of this activity, physically and intellectually. His constant interaction with graduate students and postdoctoral researchers allows his group to revisit ecological concepts and solve the problems they encounter. Because of this intensive atmosphere of discovery, his lab is recognized as an ideal workplace for graduate students and researchers. One quickly understands the great respect Legendre has for his students and collaborators, to whom he provides the intellectual room and autonomy they need.

International standing

A tremendous ambassador for the field of numerical ecology, Pierre Legendre has given lectures on all continents except Antarctica. He has presented more than 300 contributed papers at national and international conferences, including many keynote lectures, as well as more than 350 research seminars at universities and research institutes around the world. These realizations are quite remarkable for their coverage, considering the great variety of topics and themes discussed in his contributed papers and seminars.

At the international level, Pierre Legendre has seen his exceptional achievements recognized or rewarded in various ways (more details in his CV, pp. 2–3):

- Member of the editorial committees of several scientific journals.
- Director of the *NATO Advanced Research Workshop on Numerical Ecology* held at Roscoff (Brittany, France) in June 1986;
- Recipient of the *Distinguished Statistical Ecologist Award* of the *International Congress of Ecology* (INTECOL) in 1994, an honour that he shared with Sir Robert May, who was then the Chief Scientist of the UK and President of the Royal Society, and Sir Richard Southwood, Emeritus Professor of Zoology at Oxford;
- Secretary-treasurer of the *International Federation of Classification Societies*, 1988 to 1992;
- President of the *Numerical Taxomomy Conference* in 1995–1996;
- Elected Corresponding Member of *Academia Mexicana de Ciencias* (AMC) in 2016 (officially inducted in 2018);
- Honorary life membership, awarded in 2019, of the *Sociedad Ibérica de Ecología*, a new scientific society which brought together ecologists from the entire Iberian Peninsula;
- Laureate of the *2019 Alexander von Humboldt Medal for Excellence in Vegetation Science* from the International Association for Vegetation Science (IAVS);
- Invited Professor in universities in 19 countries: Australia, Belgium, Brasil, Canada, China, France, Guadeloupe, Italy, Mexico, New Caledonia, Norway, Panama, Scotland, Spain, Sweden, Switzerland, Taiwan, the USA and Wales.

Pierre Legendre has also received many of the highest Canadian prizes and awards a scientist can receive. Notably, he was elected *Fellow of the Royal Society of Canada* (Academy of Science) at the age of 45 and appointed as a *member of the Order of Canada* in 2021. He received a *Killam Research Fellowship* from the Canada Council for the Arts and the *Romanowski Medal* from the Royal Society of Canada, the *Prix Marie-Victorin* from the Government of Québec for highest achievements in research in pure and applied sciences, the *National Order of Québec*, the *Career Achievement Award* from the Canadian Council of University Biology Chairs, and the *President's Award* from the Canadian Society for Ecology and Evolution. In 2015, he was recognized as *A Legend in Canadian Fisheries Science and Management* by the Canadian Aquatic Resources Section of the American Fisheries Society.

In 2015, as part of its Centennial celebrations, the Ecological Society of America assembled a list of 115 papers published in its journals, considered to represent key contributions to the development of ideas and methods in ecology; three of these papers were signed by Pierre Legendre.

That Pierre Legendre was a *Web of Science Highly Cited Researcher* for 21 years is the most tangible testimony to his scientific influence and stature in international academia.

Changes of paradigms in science are initiated by scientists who dare to look at problems differently. Pierre Legendre launched such a change in ecology when he proposed that the spatial structure of communities should be studied in detail, as a way of understanding the underlying ecological processes. In response to this proposal, researchers are now

advocating spatial structures in new theories about the processes of recolonization and the generation of ecological variation through space, which create and maintain beta diversity in ecosystems.

In 50 years of persistent work, Pierre Legendre has developed and given substance to a new field of science, Numerical Ecology. And, as he kept developing concepts, methods and applications, he travelled around the world, teaching students and researchers how to use the new methods to help solve current ecological problems on Planet Earth.

I hereby nominate Pierre Legendre for the *Albert Einstein World Award of Science 2023,* with the conviction that this accomplished scientist and pioneer, who has forever changed the way we think about the spatial structure and processes of ecosystems, will do honour to this prestigious distinction.

Sincerely,

Daniel Jutras, O.C., Ad. E.
Rector

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February 16, 2023

Mr. Daniel Jutras
Rector of the University of Montreal

Distinguished Mr. Jutras,

I feel honored to write this reference letter in support of Prof. Pierre Legendre's nomination to the 2023 Albert Einstein World Award of Science of the World Cultural Council (WCC). I met Prof. Legendre over 20 years ago in Montreal while I was on a sabbatical leave at the University Laval in Quebec. As student and early career scientist I had read all his books on Numerical Ecology, a theme that has been a priority in environmental sciences, ecology and biology to understand the patterns of the distribution of life. The extended discussion on methodological design and ecological statistics was a very positive opportunity that evolved into a great collegial relationship and scientific interaction that transcend to generations of students in Mexico.

As part of the international scientific community, my research group and I recognize Prof. Legendre's stature one of its kind and highly inspirational. Today, when loss of biodiversity requires data, information to assess change to understand the future trend of ecosystems, his work in numerical ecology stands out. I find his contributions to knowledge, visionary, innovative and exceptionally revolutionary. Prof. Legendre is an eminence in the field of quantitative ecology and ecological statistics as attested by his scientific impact.

As founder of the field of numerical ecology, Prof Legendre has contributed extensively to its development over the past 45 years, publishing over 320 peer-reviewed papers, 22 book chapters and 12 textbooks that address and exemplify this state-of-the-art field, and maintaining it in continuous evolution. He is an international ambassador for the numerical ecology and hence highly laureated, highly Cited Researcher in Environment/Ecology with over 136 000 citations and an extraordinary Hirsch Index of 120.

It was in the late 1990s that I first met Professor Legendre and had the opportunity to discuss with him the results of my research at Instituto de Ciencias del Mar y Limnología of Universidad Nacional Autónoma de México (UNAM). This meeting initiated a fruitful collaboration between us, which has continued since then through exchange visits, seminars and teaching sessions.

I hereby would like to point out the remarkable partnership and friendship that have allowed me to collaborate with him in deep sea benthic community research and be able to discuss important ideas in aspects of macroecology. Professor Legendre came to UNAM (México) on three occasions, in 2003, 2008 and 2011, where he gave intensive one-week courses to UNAM graduate students. He came again in March 2018 for his official induction into Academia Mexicana de Ciencias (AMC) as a foreign member, where he had been elected in February 2016. In addition, he spent the week giving seminars to different departments and institutes of UNAM and discussing their research with graduate students. He also collaborated personally with some of our graduate students, giving them advice about the analysis of their thesis data, and this led to joint publications. My students and I respect and appreciate his dedication to them and to the development of his subject, Numerical ecology. On a personal note, I can say his mentoring has been very meaningful to me.

Through research seminars and short courses, he has integrated an international network of experts in themes derived and inspired by his work. The enduring contribution of Prof. Legendre is unique and in an outstanding way is a driving force in the international courageous intellectual constructs that have inspired and will continue inspiring generations to come.

I can only express myself of his outstanding work with admiration, attest to the importance of his academic work and highlight his breakthrough contributions to research and their impact on knowledge. His exceptional realizations are based on best practices and robust analytical work that support policy drafting and decision making to achieve a better understanding of the patterns of life. Prof. Legendre's ideas and research results contribute highly to society, to global intellectual and cultural life through the diverse applications of his work to find solutions to urgent environmental problems, providing a great service to humankind's wellbeing as part of the planet's biodiversity.

There is no doubt for me that his academic performance is impeccable and that Prof. Pierre Legendre deserves to be fully recognized with the 2023 Albert Einstein World Award of Science. May you require further information, please feel free to contact me. I will be very pleased to expand whys and wherefores for it.

Sincerely,

Prof. Elva Escobar-Briones, Ph.D.

Biodiversity and Macroecology Laboratory
Member of Academia Mexicana de Ciencias (AMC)

UNIVERSITETET I BERGEN
Department of Biological Sciences

Bergen, 11. February 2023

Dr Daniel Jutras
Rector, Université de Montréal
PO Box 6128, Downtown Station
Montréal, Quebec H3C 3J7

Dear Dr Jutras,

Thank you for your e-mail of 27th January inviting me to write about the nomination of Professor Pierre Legendre for the Albert Einstein World Award of Science of the World Cultural Council 2023. I am delighted to write, as Pierre Legendre is not only one of Canada's most **distinguished scientists** in the fields of biology and ecology, but he is also one of the **world leaders** in the field of numerical ecology.

I have known **Pierre Legendre** personally for about 30 years. We ran an international graduate course together on spatial data analysis. I have visited his laboratory in Montréal and we are in regular e-mail contact. One of my post-doctoral fellows, Dr Einar Heegaard, worked in Legendre's laboratory in Montréal. In 2012 Pierre and I co-authored two extensive review chapters on Clustering and partitioning and on From classical to canonical ordination in a book on Data handling and numerical techniques in palaeolimnology and palaeoecology published by Springer. I have followed with great interest Legendre's publications since about 1970. I am thus very familiar with Pierre Legendre, his work, and his standing internationally.

Pierre Legendre is, without doubt, one of the world foremost scholars in the field of numerical ecology. He has written outstanding textbooks on *Numerical Ecology* (2012, now in its third English edition) and his book with colleagues on *Numerical Ecology with R* (2018, in its second edition in the Springer Use R! series). Legendre has made many major and innovative contributions to numerical analytical problems including to analysing spatially distributed biological data; to numerical taxonomy and phylogenetics; to the testing of ecological, morphological, and phylogenetic hypotheses by means of cleverly designed permutation tests; to the analysis of data at a range of spatial scales; to the analysis of different aspects of diversity including landscape genetics and components of beta diversity; and to the interface between numerical ecology, applied statistics, and statistical theory. His research work and his publications are consistently an impressive mixture of challenging biological problems, relevant and often innovative statistical techniques, and elegant answers to the original biological problem. He has a most impressive international publication record that is widely cited world-wide with a staggering 135,000+ citations and an h-index of 120 according to Google Scholar, a clear indication of the great value and scientific importance of his work, and of his position as a world leader in the field of numerical ecology.

His research work on the rigorous numerical analysis of spatial ecological data from terrestrial, freshwater, and marine systems has been shown to be of great importance in practical problems of prediction of change, management, resilience, and stocking. Through his innovative and rigorous

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numerical approaches, he has contributed to the understanding of many environmental problems, particularly in freshwater and marine systems.

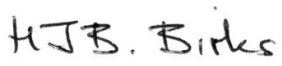
Besides being an outstanding researcher and highly productive scientific publisher, Pierre Legendre is also an extremely gifted teacher and supervisor in Montréal and elsewhere in the world. He has given many international courses around the globe. He is also extremely generous in making available to the international research community his newly developed computer software programs. Through his outstanding publications, his elegant software, his superb teaching, and his many international activities, Pierre Legendre is clearly one of the world leaders in the field of numerical ecology. When I have visited his laboratory, I have met young colleagues from, for example, Russia, China, France, Finland, Venezuela, and Australia. It is always an exciting and vibrant environment with Pierre deeply involved and actively contributing to the many research projects currently underway in his laboratory. Pierre Legendre is a truly amazing scientist who has made many major academic contributions.

He has mentored many young researchers from several countries who have gone on to develop strong international profiles in quantitative ecology including Marie-Josée Fortin, Stéphane Dray, Pedro Peres-Neto, Pierre Dutilleul, Daniel Borcard, Marti Anderson, Miquel de Cáceras, Guillaume Guenard, Fang He, and Hanna Tuomisto.

Pierre Legendre is one of a very small group of researchers who was trained as a biologist but who has made impressive and highly original contributions to the fields of applied statistics, biometrics, and spatial statistics. These have resulted in many publications in leading statistical journals such as *Journal of Classification, Environmental and Ecological Statistics, Journal of Statistical Computation and Simulation,* and *Journal of Agricultural, Biological, and Environmental Statistics*. He is very highly regarded both in the fields of numerical and quantitative ecology and evolutionary biology and applied statistics and biometrics.

Given his truly outstanding scientific contributions, publications, and influence, and his well-earned position as one of the world leaders in the field of numerical ecology (and also numerical biogeography and phylogeography), I am very delighted to support this nomination of Pierre Legendre. He is an outstanding and very deserving candidate for the Albert Einstein World Award of Science 2023. He is one of Canada's leading scientists with a superb research profile as well as being an outstanding teacher and mentor and most generous colleague. He is one of the top stars in international ecological and environmental science.

Yours sincerely,



H John B Birks

Professor Emeritus, University of Bergen
Professor Emeritus and Honorary Fellow, University College London
Corresponding (Foreign) Fellow, Royal Society of Edinburgh Foreign
Member, Norwegian Academy of Science and Letters
Foreign Member, Royal Swedish Academy of Sciences

Grounds for nominating Professor Pierre Legendre for the Albert Einstein World Award of Science 2023

Pierre Legendre is professor at Université de Montréal in Canada. He contributed broadly, extensively and uniquely to the field of Numerical ecology (see box) over the past 50 years. Indeed, he is at the origin of numerical ecology as a scientific discipline; he designed many new numerical methods of ecological data analysis, and he used them to enrich general ecology and broaden its applications. He spearheaded its development internationally, making it known to researchers and students around the world. He achieved this outstanding success by publishing textbooks and research papers, producing and distributing software for new methods, giving courses in his university and all over the world to cohorts of graduate students and large numbers of researchers, and making learned presentations.

> *Numerical Ecology* is the field of quantitative ecology devoted to the numerical analysis of multivariate community data, aimed at understanding the processes that generate and maintain biodiversity in ecosystems. Community ecologists, whose data are multivariate by nature (many species, many environmental variables), are among the primary users of these methods.
>
> An encyclopaedia article written by Pierre Legendre (2019), describing the development of Numerical Ecology, is available on his web page (publ. #2.18 in Publication list).

Professor Pierre Legendre is *the only scientist worldwide* who has been listed as *Web of Science Highly Cited Researchers* in the field of Environment/Ecology in all records published over 21 years: i.e., in 2001, then 2014–2021. His *h*-index is 120 on Google Scholar and 80 on Web of Science. Google Scholar ranks Legendre among the top five ecologists worldwide in number of peer citations, and reports that the book *Numerical Ecology* was cited over 25,000 times. He has been elected Fellow of the Royal Society of Canada (Academy of Science) in 1992 and Corresponding Member of Academia Mexicana de Ciencias in 2016. He received national and international prizes and honours listed in his CV. His approaches are uniquely original and productive, as described in the following five points.

First, Pierre Legendre not only created the new discipline of numerical ecology, he also developed it as a full-fledged component of ecology during decades of high-quality work. To do so, he published over 300 research papers on numerical ecology and community ecology in the best ecology and ecological statistics journals, plus 22 book chapters and encyclopaedia articles about applications of numerical methods to address ecological research problems. In addition to his papers, he also wrote a textbook where the expression *Numerical ecology* was proposed, in French (*Écologie numérique*, editions in 1979 and 1984) and in English (*Numerical Ecology*, editions in 1983, 1998 and 2012). The book expanded into new editions as the discipline developed into a new field of science. These books are the most widely read and cited in the world in quantitative ecology. The companion textbook, *Numerical ecology with R* (2011, 2018), written with two of his colleagues, has been translated to Chinese (2014, 2020); a Japanese edition will be published shortly in Tokyo by Kyoritsu Shuppan Co.

Second, Pierre Legendre used numerical ecology methods to break new grounds in fundamental ecology. One of his major contributions to theoretical ecology has revolutionized the way ecologists now approach the study of ecosystems by showing that spatial structures are not a statistical nuisance, but represent instead a fundamental property of ecosystems, which creates the conditions for their functioning as ecological and thermodynamic systems. The response to this 1993 *new paradigm* paper was enthusiastic (#3.69 in Publication list, 4422 citations to date), and ecologists are now advocating spatial structures in new theories about the processes of recolonization and the generation of ecological variation through space, which create and maintain *beta diversity* (defined below) in ecosystems. Pierre Legendre caused a paradigm shift in ecology by looking at spatial structures in a new way and showing how the ecological processes acting on communities could be analysed.

Third, as an ecologist with training and broad experience in multivariate statistics, Pierre Legendre developed new numerical methods to address significant ecological problems and advance the understanding of ecosystem functioning. Here is an example. A new analytical approach, called Moran's Eigenvector Maps, was developed by Pierre Legendre and ecologist Daniel Borcard in 2002 to dissect ecological patterns among spatial scales (e.g. fine, intermediate, and broad scales) to identify the processes acting at these different scales. The authors wrote a program and distributed it freely, then they replaced it with R functions distributed on CRAN in 2016. The new concept and method were adopted by the community of ecologists: this publication has been cited 2000 times (#2.133).

Other key contributions to ecology concern the ecological processes that generate and maintain the spatial differentiation of ecological communities among sites in ecosystems, called *beta diversity* by ecologists. Legendre showed in 2005 that beta diversity can be correctly estimated by the variance of the community composition data (#2.161 in Publication list, 1262 citations) and in 2013 that this beta index can be decomposed into Local Contributions and Species Contributions to Beta Diversity (#2.254 in Publication list, 650 citations). He then proposed in 2019 the idea of statistically comparing successive surveys at a set of sites to study temporal beta diversity (#2.304 in Publication list).

Fourth, as his papers and books became known, Pierre Legendre received increasing numbers of invitations to present intensive courses on numerical ecology lasting 1 to 7 days. Altogether, he has now given 86 such invited intensive courses in 56 universities, research institutes and government laboratories located in 19 countries and territories around the world: Australia, Belgium, Brazil, Canada, China, France, Guadeloupe, Italy, Mexico, New Caledonia, Norway, Panama, Scotland, Spain, Sweden, Switzerland, Taiwan, the USA and Wales. In addition, 60 researchers in 23 countries working on the North and South Atlantic attended a Legendre online course on 15–18 June 2021.

He has prepared and recorded a course entitled *Numerical ecology in 8 lessons*, featuring 16h45 of recorded lectures plus practical exercises, which was put online in May 2021 by Université de Montréal. This course is available to students and researchers around the world for a very moderate fee. Pierre Legendre's generous approach to the dissemination of numerical ecology is very original, and much appreciated by students and colleagues. In this vein, he received the *Excellence in Teaching Award* of Université de Montréal, and a similar award from the Faculty of Arts and Science.

Fifth, several of the ecological problems investigated by Pierre Legendre are of foremost social importance. They are relevant to the global, interrelated problems of biodiversity loss and effects of climate change, touching losses in marine resources and forest biodiversity. An example is his work about natural forest communities in Canada moving to new locations in response to climate change (#2.304 and #2.308 in Publication list).

Professor Pierre Legendre is a very imaginative and creative researcher, who consistently produced new concepts and new numerical methods that deeply influenced the progress of ecology. He is an enthusiastic promoter of fundamental ecology and numerical analysis in the classroom, in scholarly venues, and now on the web. The nominee is a scientist and a teacher. He dedicated his career to working with students and colleagues, creating new concepts and methods and applying them to ecological questions that have great social relevance. He is working under the assumption that sharing scientific knowledge with scientists and graduate students from different countries will increase mutual understanding among peoples and the likelihood of peace on planet Earth. After developing a new subfield of ecological sciences, he travelled the world sharing his knowledge with scientists and graduate students, responding to invitations extended to him by many universities and research institutes where his work was known through the scientific literature. This is also a measure of his notoriety as a numerical ecologist and a teacher.

Pierre Legendre
Curriculum vitae

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https://en.wikipedia.org/wiki/Pierre_Legendre_(ecologist)

Biographical information

1971	Ph.D. in Evolutionary Biology, Dept. of Biology, Univ. of Colorado (Boulder), USA.
1969	M.Sc. in Zoology, Department of Zoology, McGill University, QC, Canada.
1965–67	Two years of B.Sc. in biological sciences, Université de Montréal, QC, Canada.
1965	B.A., Collège Saint-Viateur, Montréal (college affiliated to Université de Montréal).
1946	Born in Montréalec, QC, Canada.

Academic employment history

1984–	Full professor, Département de sciences biologiques, Université de Montréal.
1980–84	Associate professor, Département de sciences biologiques, Université de Montréal.
1980	Professor, Département de physique, Université du Québec à Montréal.
1973–80	Research director, Centre de recherche en sciences de l'environnement, Université du Québec à Montréal. NSERC Research Associate, 1977–1980.
1972–73	Research associate, Centre de recherche écologique, Université du Québec à Montréal.
1971–72	Postdoctoral fellow (CNRC), Genetiska Institutionen, Lunds Universitet, Sweden.

Scientific interests

Pierre Legendre is an ecologist and a founder of the field of *Numerical ecology*, a branch of community ecology that he founded and to which he has contributed extensively over the past 50 years. His research concerns in particular the ecological and biogeographic processes that generate and organize biodiversity through space and time. An important component of his research in fundamental ecology is the development of quantitative methods to analyse multivariate ecological data. He works at the moment on adapting and transferring the methods developed in spatial community ecology to landscape genetics, in particular for the study of genetic beta diversity.

Scientific Prizes and Distinctions

Scientific prizes

• 2019 – Laureate of the *2019 Alexander von Humboldt Medal for Excellence in Vegetation Science* of the International Association for Vegetation Science (IAVS), *"for his valuable contributions in the field of numerical ecology"*. Medal presented on 16 July 2019 during the 62th Annual IAVS Symposium in Bremen, Germany.

• 2015 – Laureate of the *Adrien-Pouliot* Prize (for scientific cooperation with France), *Association francophone pour le savoir*[1] and the French Consulate in Québec City and Ministère des Relations internationales et de la Francophonie du Québec. Award presented in Montréal, 22 October 2015.

• 2015 – *Legend in Canadian Fisheries Science and Management* "in recognition and appreciation of contributions to fisheries science". Presented to Pierre Legendre by the *Canadian Aquatic Resources Section* of the *American Fisheries Society* (AFS), 15 May 2015. Award announced during the 145th annual conference of the AFS in Portland, Oregon, 16–20 August 2015.

• 2013 – Laureate of the Canadian Society for Ecology and Evolution(CSEE) *President's Award*. Kelowna, British Columbia, 14 May 2013, during the CSEE annual meeting.

• 2012 – Laureate of the Canadian Council of University Biology Chairs *Career Achievement Award*. University of Waterloo, 16 November 2012.

• 2005 – Laureate of *Prix Marie-Victorin*, the annual prize of the Government of Québec "*for highest achievements in research in natural sciences and engineering*". Québec, 8 November 2005.

• 1999 – Laureate of the *Twentieth Century Distinguished Service Award* "for outstanding contribution to the synergistic development and direction of statistics, ecology, environment and society", awarded by the Ninth Lukacs Symposium "*Frontiers of Environmental and Ecological Statistics for the 21st Century"*. Bowling Green State University, Bowling Green, Ohio, 24 April 1999.

• 1995 – Laureate (2nd recipient) of the Romanowski Medal (environmental science) of the *Royal Society of Canada*. Saint Paul University, Ottawa, 16 June 1995.

• 1994 – Laureate of the *Distinguished Statistical Ecologist Award* of the *International Congress of Ecology* (INTECOL). Manchester, England, 22 August 1994.

• 1986 – Laureate of the *Michel-Jurdant* prize for Environment Sciences, *Association canadienne-française pour l'avancement des sciences* (Acfas)[1]. Montréal, 12 May 1986.

Teaching prizes

• 2011 – Laureate of Université de Montréal *Excellence in Teaching Award*, *Full Professor category*. Award presented on 27 May 2011.

• 2011 – Laureate of the *Excellence in Teaching Award, Science Sector* of the Faculty of Arts and Science, Université de Montréal. Award presented on 14 June 2011.

[1] Acfas was formerly called *Association canadienne-française pour l'avancement des sciences*; despite its new name, the Society kept the acronym Acfas.

Other distinctions

• 2021 – *Membre of the Order of Canada*, 24 Septembre 2021. Web page of the announcement: https://www.gg.ca/en/activities/2021/governor-general-announces-135-new-appointments-order-canada

• *Web of Science Highly Cited Researcher* in all lists published during 21 years, firstly in 2001 then every year from 2014 to 2021; at first by the Institute for Scientific Information (USA), then by Thomson Reuters (USA) and, since 2017, by Clarivate (USA and UK).

• 2019 – *Honorary life membership* in the Sociedad Ibérica de Ecología, a new scientific society which brought together ecologists from the whole Iberian Peninsula. In Barcelona, 7 February 2019.

• 2016 – Elected *Corresponding Member* of Academia Mexicana de Ciencias (AMC), 5 February 2016. Officially inducted in México City on 6 March 2018.

• 2007 – Officer of the *National Order of Québec*. Presentation of insignia: Québec, 18 June 2008.

• 1992 – Elected *Fellow of the Royal Society of Canada (Academy of Science).* Presentation of insignia: Ottawa, 21 May 1992.

• 1989-1991 – *Killam Research Fellow*, Canada Council for the Arts.

Scientific production in career

TYPES OF PRODUCTION	TOTAL NUMBER
Number of books and chapters	13 books / 22 book chapters
Number of refereed articles	Journal articles: 322 Conference proceedings and data papers: 24
Number of citations	Web of Science: 49 332 / Google Scholar: 136 106
Hirsch (*h*) index	Web of Science: 80 / Google Scholar: 120
Package versions in R language	114 Version of 9 different R packages available on https://cran.r-project.org
Papers at conferences	306 (including 58 keynote addresses)
Research seminars	360
Short courses	86 (in 56 universities and research institutes located in 19 countries)
International working groups	19

Professor Pierre Legendre —
Ten most important papers

Note – One book, then nine papers in chronological order. Numbers of citations are from Google Scholar, 3 February 2023 (https://scholar.google.ca/citations?User= daJE-XsAAAAJ).

1. Legendre, P. & L. Legendre. 2012. *Numerical ecology, 3rd English edition.* Elsevier Science BV, Amsterdam. xvi + 990 pp. ISBN-13: 978-0444538680. Two editions in French (Masson, Paris) and three in English (Elsevier, Amsterdam).

   => [*25 873 citations* for all editions.] The most widely used book on numerical ecology, based on 25 years of teaching experience and discussions with colleagues at scientific conferences, by the authors who defined the field of *Numerical ecology*. This book is used by community ecologists in all universities and research institutes throughout the world.

2. Borcard, D., P. Legendre & P. Drapeau. 1992. Partialling out the spatial component of ecological variation. *Ecology* 73: 1045-1055. https://doi.org/10.2307/1940179

   => [*4791 citations.*] First paper to describe *multivariate variation partitioning*, which estimates the proportions of variation of community composition data explained by two or more tables of explanatory variables, e.g. environmental, climatic, geomorphological, geological and spatial data matrices. The method is implemented in function varpart.R of the *vegan* package.

3. Legendre, P. 1993. Spatial autocorrelation: trouble or new paradigm? *Ecology* 74: 1659-1673. https://doi.org/10.2307/1939924

   => [*4422 citations.*] In this paper, Legendre developed a new paradigm for community ecology, that spatial relationships are key to understanding the ecological processes that organize biodiversity through space. The paper sent a message to young researchers, that the development of new ideas in research is not linear but may include unexpected furcations. This key paper was the subject of a publication by history of ecology researcher Hari Shridar who interviewed authors of vintage papers in ecology and evolution. See: https://reflectionsonpaperspast.wordpress.com/2020/05/15/revisiting-legendre-1993/.

4. Dufrêne, M. & P. Legendre. 1997. Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* 67: 345-366. https://doi.org/10.2307/2963459

   => [*9638 citations.*] The identification of indicator species (indicating particular environmental conditions, which is useful in environmental monitoring, conservation and management) has been a traditional question in ecology and biogeography. This problem was revisited and formalized in this paper proposing a statistically sound method of identifying indicator species and testing their significance. This method was later expanded to include other forms of indicator species indices, in a paper by De Cáceres & Legendre published in 2009.

5. Legendre, P. & M. J. Anderson. 1999. Distance-based redundancy analysis: testing multispecies responses in multifactorial ecological experiments. *Ecological Monographs* 69: 1-24. https://doi.org/10.2307/2657192

   => [*2434 citations.*] This paper explained for the first time how to compute canonical redundancy analysis from a dissimilarity matrix (**D**) computed using double-zero asymmetric coefficients, which are appropriate for community composition and other frequency data. Canonical analysis relates multivariate response data, such as community composition, to explanatory data, which may represent analysis-of-variance factors, as shown in this paper.

6. Legendre, P. & E. D. Gallagher. 2001. Ecologically meaningful transformations for ordination of species data. *Oecologia* 129: 271-280. https://www.jstor.org/stable/4223083

=> [*4918 citations.*] Community composition data can be transformed using a family of mathematical transformations that make the data usable in linear methods of multivariate analysis such as principal component ordination or multivariate analysis of variance. This paper describes the first transformations that are part of a new family, later expanded by Legendre & Borcard (2018).

7. Borcard, D. & P. Legendre. 2002. All-scale spatial analysis of ecological data by means of principal coordinates of neighbour matrices. *Ecological Modelling* 153: 51-68. https://doi.org/10.1016/S0304-3800(01)00501-4

   => [*2002 citations.*] Spatial eigenfunction modelling was first proposed in this paper. A geographic distance matrix is decomposed mathematically, producing a series of vectors (eigenfunctions) that model as many different spatial scales. This amounts to a Fourier analysis of the spatial relationships among the sites. It can operate on sites forming a regular grid, as found in fully inventoried forest plots, or on irregularly-positioned sites, like lakes and ponds scattered throughout a landscape. The new method allowed ecologists to test hypotheses about the processes organizing biodiversity through geographic space, partitioning the variation between environmental variables and spatial processes operating at a variety of spatial scales.

8. Legendre, P., D. Borcard & P. R. Peres-Neto. 2005. Analyzing diversity: partitioning the spatial variation of community composition data. *Ecological Monographs* 75: 435-450. https://doi.org/10.1890/05-0549

   => [*1432 citations.*] The simulation study reported in this paper showed that the proper statistical procedure for partitioning the spatial variation of community composition data among environmental and spatial components, described in paper #2 in 1992 and used for testing hypotheses about the origin and maintenance of variation in community composition among sites, is canonical partitioning, *not* partitioning based upon dissimilarity matrices and Mantel tests.

9. Legendre, P. & M. De Cáceres. 2013. Beta diversity as the variance of community data: dissimilarity coefficients and partitioning. *Ecology Letters* 16: 951-963. https://dx.doi.org/10.1111/ele.12141

   => [*944 citations.*] Among the ways of measuring beta diversity (i.e., the spatial variation of community composition data), the total variance of the community matrix provides an accurate and most useful estimate. It can be computed on transformed community data (paper #9) and on dissimilarity matrices appropriate for community data. The total variance can then be partitioned among sites and among species to identify the sites and species that contribute the most to beta diversity. This method links the ecological concept of beta diversity to well-known methods of multivariate analysis of community composition data used by ecologists, like principal component and canonical analysis, which also partition the total variance.

10. Legendre, P. 2019. A temporal beta-diversity index to identify sites that have changed in exceptional ways in space-time surveys. *Ecology and Evolution* 9: 3500–3514. https://doi.org/10.1002/ece3.4984

    => [*105 citations.*] A new method for the comparison of ecological surveys at several sites, repeated through time, was described by Legendre in this paper. Studies of this type are presently conducted around the world by large teams of ecologists, governmental and academic, to assess the effects of climate change and other anthropic pressures on the environment. This method is likely to become highly praised by ecologists who are collecting this type of data. Software in R implementing the new method was written by Legendre and made available in the R package *adespatial*.

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Pierre Legendre
Scientific publications

1. Books

1.1 Legendre, L. & P. Legendre. 1979. Écologie numérique. Tome 1: Le traitement multiple des données écologiques. Préface du Pr. Ramón Margalef. Collection d'Écologie no 12. Masson, Paris et les Presses de l'Université du Québec. xiv + 197 p. — *[Numerical ecology, Volume 1: The multiple processing of ecological data. Preface by Prof. Ramón Margalef. Ecology Collection No. 12. Masson, Paris and Presses de l'Université du Québec. xiv + 197 pp.]* — Equal contributions of the authors, listed in alphabetic order.

1.2 Legendre, L. & P. Legendre. 1979. Écologie numérique. Tome 2: La structure des données écologiques. Collection d'Écologie no 13. Masson, Paris et Presses de l'Université du Québec. viii + 254 p. — *[Numerical ecology, Volume 2: The structure of ecological data. Ecology Collection No. 13. Masson, Paris and Presses de l'Université du Québec.* viii + 254 *pp.]* — Equal contributions of the authors, listed in alphabetic order.

1.3 Legendre, L. & P. Legendre. 1983. Numerical ecology. Developments in environmental modelling, 3. Elsevier Scientific Publ. Co., Amsterdam Netherlands. xvi + 419 pp. — Equal contributions of the authors, listed in alphabetic order.

1.4 Legendre, L. & P. Legendre. 1984. Écologie numérique, deuxième édition revue et augmentée. Tome 1: Le traitement multiple des données écologiques. Préface du Pr. Ramón Margalef. Masson, Paris et les Presses de l'Université du Québec. xv + 260 p. — *[Numerical ecology, Second revised and expanded ediiton. Volume 1: The multiple processing of ecological data. Preface by Prof. Ramón Margalef. Ecology Collection No. 12. Masson, Paris and Presses de l'Université du Québec. xv + 260 pp.]* — Equal contributions of the authors, listed in alphabetic order.

1.5 Legendre, L. & P. Legendre. 1984. Écologie numérique, deuxième édition revue et augmentée. Tome 2: La structure des données écologiques. Masson, Paris et les Presses de l'Université du Québec. viii + 335 p. — *[Numerical ecology, Second revised and expanded ediiton. Volume 2: The structure of ecological data. Ecology Collection No. 13. Masson, Paris and Presses de l'Université du Québec.* viii + 335 *pp.]* — Equal contributions of the authors, listed in alphabetic order.

1.6 Legendre, P. & L. Legendre [eds.] 1987. Developments in numerical ecology. NATO ASI series, Vol. G-14. Springer-Verlag, Berlin. xi + 585 pages.

1.7 Legendre, P. & L. Legendre. 1998. Numerical ecology, 2nd English edition. Prefaces by Prof. F. James Rohlf and by Prof. Ramón Margalef. Elsevier Science BV, Amsterdam. xv + 853 pages. <http://www.fas.umontreal.ca/biol/legendre/numecol.html>

1.8 Borcard, D., F. Gillet & P. Legendre. 2011. Numerical ecology with R. Use R! series, Springer Science, New York. xi + 306 pp. ISBN: 978-1-4419-7975-9. e-ISBN: 978-1-4419-7976-6.

1.9 Legendre, P. & L. Legendre. 2012. Numerical ecology, 3rd English edition. Developments in Environmental Modelling, Vol. 24. Elsevier Science BV, Amsterdam. xiv + 990 pp. ISBN-13: 978-0444538680. <http://www.elsevierdirect.com/ISBN/9780444538680/Numerical-Ecology>

1.10 Borcard, D., F. Gillet & P. Legendre. 2014. Numerical ecology with R, Chinese edition (translation : J. Lai, Institute of Botany, Chinese Academy of Sciences). Higher Education Press, Beijing. V + 275 pp. (Published May 14, 2014).

1.11 Borcard, D., F. Gillet & P. Legendre. 2018. Numerical ecology with R, Second edition. Use R! series, Springer International Publishing AG. xv + 435 pp. ISBN 978-3-319-71403-5, eBook ISBN 978-3-319-71404-2. (Published 20 March 2018.) Price: $74.99 Cad; eBook: $59.99 (http://www.springer.com/us/book/9783319714035).

1.12 Borcard, D., F. Gillet & P. Legendre. 2020. Numerical ecology with R, 2nd Chinese edition (translation: J. Lai, Institute of Botany, Chinese Academy of Sciences). Higher Education Press, Beijing. xviii + 432 pp. + 10 colour figures. (Published 9 May 2020).

1.13 Borcard, D., F. Gillet & P. Legendre. 2023. Numerical ecology with R (Rによる数値生態学), Japanese edition. Kyoritsu Shuppan Co. Ltd, Tokyo. Publication date: 28 February 2023.

2. Refereed book chapters

Reprints of these papers, if available in pdf: *http://numericalecology.com/Reprints/*

2.1 Legendre, L. & P. Legendre. 1978. Associations. Pp. 261-272 in: Phytoplankton Manual. Monographs on oceanographic methodology no 6. UNESCO, Paris. 338 pp.

2.2 Legendre, P. & L. Legendre. 1982. Échantillonnage et traitement des données. Ch. 3 (pp. 163-216) *in*: S. Frontier [éd.] Stratégies d'échantillonnage en écologie. Collection d'Écologie no 16. Masson, Paris. xviii + 494 p. — *[Sampling and data processing. Ch. 3 (pp. 163-216) in: S. Frontier [ed.] Sampling strategies in ecology. Ecology Collection No. 16. Masson, Paris. xviii + 494 pp.]*

2.3 Legendre, P. 1983. Numerical ecology: developments and recent trends. 505-523 in: J. Felsenstein [ed.] Numerical taxonomy. Nato Advanced Study Institute Series G (Ecological Sciences), No. 1. x + 644 p. [Invited paper.]

2.4 Legendre, P. 1987. Constrained clustering. Pp. 289-307 in: P. Legendre & L. Legendre [eds.] Developments in numerical ecology. NATO ASI series, Vol. G-14. Springer-Verlag, Berlin. xi + 585 pages. [Invited paper.]

2.5 Legendre, P. 1990. Quantitative methods and biogeographic analysis. Pp. 9-34 in: Garbary, D. J. & G. R. South (eds.) Evolutionary biogeography of the marine algae of the North Atlantic. NATO ASI Series, Vol. G 22. Springer-Verlag, Berlin.

2.6 Lapointe, F.-J. & P. Legendre. 1996. Evolution of the marsupial brain: Does it reflect the evolution of behavior? Chapter 11, pp. 187-212 *in*: Animals and their environment – A tribute to Paul Pirlot (T. Cabana, editor). Éditions Orbis Publishing, Frelighsburg, Canada.

2.7 Renaud, J. & P. Legendre. 1997. Nouveaux immigrants et localisation résidentielle. P. 103–127 *in:* D. Meintel, V. Piché, D. Juteau et S. Fortin [éds.] Le quartier Côte-des-Neiges à Montréal – Les interfaces de la pluriethnicité. L'Harmattan, Paris. 323 p. — *[New immigrants and residential location. Pp. 103–127 in: D. Meintel, V. Piché, D. Juteau and S. Fortin [eds.] The Côte-des-Neiges quarter in Montréal – The interfaces of multi-ethnicity. L'Harmattan, Paris. 323 pp.]*

2.8 Legendre, P. et D. Borcard. 2006. Quelles sont les échelles spatiales importantes dans un écosystème ? Chapitre 19 (p. 425-442) *in*: J.-J. Droesbeke, M. Lejeune et G. Saporta (éds), *Analyse statistique de données spatiales.* Éditions TECHNIP, Paris. 468 pages. ISBN 10 : 2710808730. — *[What are the important spatial scales in an ecosystem? Chapter 19 (pp. 425-442) in: J.-J. Droesbeke, M. Lejeune and G. Saporta (eds), Statistical analysis of spatial data. Éditions TECHNIP, Paris. 468 pp.]*

2.9 Makarenkov, V., D. Kevorkov & P. Legendre. 2006. Phylogenetic network construction approaches. Pp. 61-97 in: *Applied Mycology and Biotechnology, Volume 6: Bioinformatics*. Elsevier Science B. V., Amsterdam.

2.10 Legendre, P. 2007. Préface. Pp. III-IV *in* Scherrer, B. *Biostatistique*. Chenelière Éducation, Montréal. — *[Preface. Pp. III-IV in Scherrer, B. Biostatistics. Chenelière Éducation, Montréal]*

2.11 Legendre, P. 2010. Coefficient of concordance. Pp. 164-169 in: *Encyclopedia of Research Design, Vol. 1.* N. J. Salkind, ed. SAGE Publications, Inc., Los Angeles. 1776 pp. ISBN: 9781412961271. [Published in July 2010.]

2.12 Legendre, P. & H. J. B. Birks. 2012. Clustering and partitioning. Chapter 7, pp. 167-200 in: *Tracking Environmental Change using Lake Sediments, Volume 5: Data handling and numerical techniques.* H. J. B. Birks, A. F. Lotter, S. Juggins & J. P. Smol [eds.]. Springer, Dordrecht, The Netherlands. xi + 716 pp. [Published April 8, 2012.]

2.13 Legendre, P. & H. J. B. Birks. 2012. From classical to canonical ordination. Chapter 8, pp. 201-248 in: *Tracking Environmental Change using Lake Sediments, Volume 5: Data handling and numerical techniques.* H. J. B. Birks, A. F. Lotter, S. Juggins & J. P. Smol [eds.]. Springer, Dordrecht, The Netherlands. xi + 716 pp. [Published April 8, 2012.]

2.14 Fortin, M.-J., P. Drapeau & P. Legendre. 2012. Spatial autocorrelation and sampling design in plant ecology. Pp. 209-222 *in*: G. Grabherr, L. Mucina, M.B. Dale & C.J.F. ter Braak [eds.] *Progress in Theoretical Vegetation Science*. Advances in Vegetation Science, Vol. 11. Springer.

2.15 Legendre, P. 2013. Indicator species: computation. Pp. 264-268 in: *Encyclopedia of Biodiversity, 2nd edition.* Simon Levin [ed.] Academic Press, Waltham, MA, USA. [Published February 21, 2013.]

2.16 Boc, A., P. Legendre & V. Makarenkov. 2013. An efficient algorithm for the detection and classification of horizontal gene transfer events and identification of mosaic genes. Pp. 253-260 *in*: B. Lausen, D. Van den Poel & A. Ultsch [eds] *Algorithms from and for Nature and Life: Classification and data analysis*. Springer International Publishing, Switzerland. [Published September 10, 2013] doi:10.1007/978-3-319-00035-0_25.

2.17 Makarenkov, V., A. Boc & P. Legendre. 2014. A new algorithm for inferring hybridization events based on the detection of horizontal gene transfers. Pp. 273–293 *in*: F. Aleskerov, B. Goldengorin & P. M. Pardalos [eds.] *Clusters, Orders, and Trees: Methods and Applications — In Honor of Boris Mirkin's 70th Birthday*. Springer Optimization and Its Applications, 92. Springer, New York.

2.18 Legendre, P. 2019. Numerical ecology. Pp. 487-493 in: *Encyclopedia of Ecology, 2nd edition* (B. D. Fath, Editor-in-Chief). Volume: *Earth systems and environmental sciences.* Elsevier Inc., Oxford, England. https://doi.org/10.1016/B978-0-12-409548-9.10595-0. View the pdf: http://www.numericalecology.com/Reprints/Legendre_Numerical_Ecology_EoE2_2019.pdf

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4. Submitted papers (January 2023)

4.1 Wittische, J. P. Legendre & P. James. Detecting temporal changes in genetic diversity: a new tool for molecular ecology studies with repeated surveys. *Molecular Ecology Resources* (submitted, 04 October 2021, MER-21-0479; with corrections, February 2023).

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