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Ingmar Prucha's contributions to economics and econometrics

Guido Kuersteiner[1] · **John Chao**[1]

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Abstract This short note honors Ingmar Prucha's many scientific contributions in econometrics and empirical economics. We conclude with a few more personal remarks.

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JEL Classification C00 · C30 · C31 · C33

1 Introduction

We are very fortunate to have Ingmar Prucha as our colleague and collaborator. It is therefore a special honor for us to write this article in celebration of Ingmar's many contributions to research and scholarship. We begin our exposé with a brief account of Ingmar's education and career as a researcher and educator. We also discuss his numerous editorial positions and honors received over the years. The main portion of our article then discusses Ingmar's many contributions to research in a variety of areas in economics and econometrics. We conclude with two more personal accounts.

✉ Guido Kuersteiner
kuersteiner@econ.umd.edu

John Chao
chao@econ.umd.edu

[1] Department of Economics, University of Maryland, 3145 Tydings Hall, 7343 Preinkert Dr., College Park, MD 20742, USA

2 Education and career

Ingmar Prucha was born in Austria and studied at the Technische Universität Wien in Vienna where he graduated with a degree in Engineering. He earned a postgraduate degree in economics from the Institute for Advanced Studies in Vienna and in 1977 a doctorate in Mathematical Economics from the Technische Universität Wien. His dissertation was on a model for the Austrian economy with special emphasis on medium-term aspects and the measurement of the capital stock.

Ingmar Prucha's first position as a researcher was at the Institute for Advanced Studies in Vienna where he worked until 1980. He was part of the Link project lead by Nobel Laureate Lawrence Klein. It is at the institute during that time where he met his long-term collaborator and friend Harry Kelejian with whom he later coauthored countless important contributions in spatial econometrics. During that time, he also held visiting research positions at the University of Pennsylvania, the University of Maryland and New York University until becoming an Assistant Professor in Economics at the University of Maryland in 1981. He stayed in the Economics Department at the University of Maryland throughout his entire career to this date. He became an Associate Professor in 1987 and a full professor in 1991. In 2014, Ingmar Prucha was named a Distinguished University Professor at the University of Maryland, a recognition awarded only to the most accomplished scholars. In 2008, he was also named an Honorary Professor at the University of Innsbruck in Austria. Ingmar Prucha has held numerous visiting positions around the world, including the NBER, the University of Konstanz, the Institute of Advanced Studies, the University of Innsbruck, the CESIfo Institute in Munich, the Singapore Management University, the University of Innsbruck, the Spatial Econometric Advanced Institute in Rome, ETH in Zurich, American University, and the Vienna Graduate School.

Ingmar Prucha holds numerous editorial positions. He is an associate editor at *Econometric Theory, Journal of Econometrics* and *Regional Science and Urban Economics*. He is a member of the editorial board of *Letters in Spatial and Resource Sciences*, and in the past served as a member of the editorial board for *Empirical Economics* and *Empirica*. In addition to these positions, he served as guest editor for the *Journal of Econometrics* on a volume titled " Contributions to Econometrics, Time Series Analysis, and Systems Identification: A Festschrift in Honor of Manfred Deistler" jointly with Benedikt Pötscher, and a volume titled " Analysis of Spatially Dependent Data" jointly with Badi Baltagi and H.H. Kelejian. For *Spatial Economic Analysis*, he served as guest editor jointly with Giuseppe Arbia for a special issue titled " Contributions to Spatial Analysis: A Festschrift in Honor of Harry Kelejian" and for *The Review of Regional Studies* he was a guest editor jointly with Giuseppe Arbia and Gianfranco Piras for a special issue entitled: "Spatial Econometric Association Special Issue."

Ingmar Prucha is a Fellow of the *Journal of Econometrics,* and a founding Fellow and member of the board of directors of the *Spatial Econometrics Association*. He won numerous teaching awards at the University of Maryland and was invited to be a keynote speaker at conferences around the world. He has published over 60 peer-reviewed articles, four of them in *Econometrica*, and 13 in the *Journal of Econometrics*. He also coauthored a widely cited monograph with Benedikt Pötscher.

3 Research contributions

Ingmar Prucha contributed to a large number of research areas in economics, both applied and theoretical. His most cited work is in spatial econometrics, general asymptotic theory, empirical work on the determinants of physical capital investment and R&D expenditures. During the last two decades, Ingmar worked mostly on econometric methods for spatial models and in particular on so called Cliff–Ord-type spatial models. Building on Whittle (1954), Cliff and Ord (1973, 1981) introduced a widely influential idea for modeling spatial network interactions in the form of spatial lags into the regional science literature. Spatial lags model spatial network interactions in terms of weighted sums, where the weights are inversely related to some measure of distance. Anselin (1988) work provides seminal extensions. Cliff–Ord-type models utilize a measure of distance that describes the connection between units. The distance measure can relate to geography, or other spaces such as product and social space. Harry Kelejian introduced Ingmar Prucha to this class of models, which was not well known in economics at the time. Together, they pioneered applications of spatial models in economics in the mid-1990s, and their work was instrumental in the original development of formal methods of inference. Until the mid-1990s, the prevailing estimation method for those models was maximum likelihood, but a formal analysis of the statistical properties was mostly lacking at that time due to a lack of appropriate limit theorems.

Among his many publications on spatial econometric methods, Ingmar Prucha's most well-known work is on GMM estimation techniques for Cliff–Ord models. Some of these models are quite difficult to estimate with maximum likelihood or pseudo-likelihood methods. This is due to the fact that the model implied correlation structure of the underlying disturbances is highly nonlinear in the parameters and depends on large dimensional inverses that may be of the same order as the sample size. These theoretical properties of the Cliff–Ord model pose severe computational problems for likelihood estimators, especially in large sample sizes. The GMM estimators that Ingmar Prucha has developed throughout his career do not suffer from these computational difficulties in the same way that maximum likelihood estimators do and are often significantly simpler to implement. These are important advantages, especially in light of recent applications of spatial methods to network data which can involve very substantial sample sizes.

Two of Ingmar Prucha's most cited papers are "A generalized spatial two-stage least squares procedure for estimating a spatial autoregressive model with autoregressive disturbances" published in *The Journal of Real Estate Finance and Economics* in 1998 and "A Generalized Moments Estimator for the Autoregressive Parameter in a Spatial Model" published in the *International Economic Review* in 1999. Both of these papers, which are joint with Harry Kelejian, develop simple to implement and compute estimators for the Cliff–Ord model. Even though published a year later, the second paper predates the first one in terms of when the research for it was done and provides the theoretical foundation for the two-stage least-square procedure. The 1999 paper proposes an estimator based on generalized methods of moments identification schemes. More specifically, restrictions on the error distribution of the reduced form innovations are exploited to formulate a set of moment conditions that identify the

spatial autoregressive parameter. The moment conditions related to spatial parameters are quadratic moment restrictions. The fact that nonlinear moment restrictions can be used to identify spatial parameters is an important insight that continues to play a significant role in the literature on spatial models to this date. The paper constitutes an important departure from the literature at the time which focused mainly on maximum likelihood-based inference. The authors make a convincing case that these likelihood-based approaches may become infeasible in large data sets where their estimators continue to be implementable with ease. A major contribution of the 1999 paper is a formal set of assumptions for spatial dependence and provide rigorous proofs of consistency and asymptotic normality of their estimators under these conditions. The catalogue of assumptions that formalizes the notion of "fading memory," independent of the ordering of the data, is now widely used in the spatial literature. The 1998 paper develops two-stage least-square estimators and builds on the results of the 1999 paper. The two-stage least-square estimator is based on the insight that the reduced form of the model can be given a series expansions in powers of the spatial weight matrix. It is the form of this series expansion that provides a selection of valid and powerful instruments. The 1998 paper was an invited contribution to a special volume on Spatial Statistics and Real Estate of the *The Journal of Real Estate Finance and Economics.*

The idea of computationally efficient IV estimators in spatial models with spatial autoregressive terms and autoregressive disturbances is further explored in a paper with Kelejian and Yuzefovich, published in *Advances in Econometrics* in 2004. In this paper, an optimal IV estimator based on a series expansion of the reduced form is proposed and shown to have good properties when compared with the maximum likelihood estimator in Monte Carlo simulations.

Ingmar Prucha, in collaboration with Harry Kelejian, made numerous contributions to the spatial literature related to relaxing some of the strong assumptions imposed on the errors and covariates. The paper "Specification and Estimation of Spatial Autoregressive Models with Autoregressive and Heteroskedastic Disturbances," published in the *Journal of Econometrics* in 2010, considers the two-stage least-square and GMM estimators developed in earlier work under weaker assumptions allowing for heteroskedastic model errors. One of the challenges in implementing the GMM estimator is to account for heterogeneous moment conditions. The paper also addresses how heterogeneity affects the limiting distributions of the estimators under investigation. Another important contribution of Ingmar Prucha and Harry Kelejian is their 2007 paper titled "HAC Estimation in a Spatial Framework" published in the *Journal of Econometrics*. This paper considers consistent covariance matrix estimation in the context of spatially observed data where the error terms are spatially correlated in an unspecified way. The paper then uses these results to construct a feasible instrumental variables estimator for a Cliff–Ord model where the error may display general patterns of spatial correlation and heteroskedasticity. Clearly, this is a very important contribution to a literature that in general has relied on rather strong restrictions and many functional form assumptions. Allowing for nonparametrically specified correlation and heteroskedasticity in the errors significantly enhances practical applicability of spatial models. Related work is also available in Arraiz, Drukker, Kelejian and Prucha entitled "A spatial Cliff–Ord-type model with heteroskedastic innovations: small and large sample results" and published in the *Journal of Regional Science* in 2010. In this

paper, the authors extend the HAC covariance matrix estimators to GMM- and IV-type estimators and demonstrate feasible implementation of these procedures when the errors of the spatial model are heteroskedastic.

Another very influential paper is "On the asymptotic distribution of the Moran I test statistic with applications" which is joint work with Harry Kelejian and appeared in the *Journal of Econometrics* in 2001. In this paper, the authors analyze the asymptotic properties of Moran's I test for spatial correlation. The test dates back to 1950, but theoretical results for it were sparse and obtained under restrictive conditions. In order to analyze the limiting distribution of the test statistic, the authors first develop a generic central limit theorem for linear–quadratic forms while allowing for general heterogeneity in the error terms. Their contribution significantly extended existing results in the literature that were confined to the analysis of iid errors. The general limit theory is then used to develop specific tests for spatial dependence in a number of linear and nonlinear models, including selection and discrete choice models as well as spatial models. Limit theory for linear–quadratic forms plays a central role in the analysis of spatial models because in important cases, including peer effect models, both linear and quadratic moment conditions are required for identification. Without the assumption of full independence and in some cases homoskedasticity and Gaussianity, the limiting distributions can be challenging to analyze. Ingmar Prucha has made very important contributions to the theory of such limiting results under increasingly more general conditions, and this paper is an important corner stone in this line of research.

Peer effect models have focused on capturing group effects in regression settings with included group averages. The spatial literature contains these models as special cases. Ingmar Prucha has made important contributions to this specific class of spatial models. In an early paper titled "2SLS and OLS in a spatial autoregressive model with equal spatial weights" Kelejian and Prucha analyze identification failure of group effect models where the number of equally weighted units grows asymptotically with the sample size. In their case, averages that leave out the specific individual are considered and shown to lead to inconsistent estimates when the number of equally weighted units is proportional to the sample. They also show that a panel model can be used to overcome identification failures. Finite sample results are considered in a paper with Kelejian and Yuzefovich that appeared in the *Journal of Regional Science* in 2006. The analysis of networks, including social networks, has developed into a major research area in economics and econometrics. Ingmar Prucha, in joint work with others, continues to actively contribute to this important area. Current work includes empirical and theoretical work on peer effect models with network formation and heterogeneous group effects. Joint research with Guido Kuersteiner and David Drukker form Stata, titled " New Methods of Inference and Software for the Empirical Analysis of Network Generated Data" just recently received funding from NIH.

Another important class of spatial models Ingmar Prucha has worked on are panel models with a spatial component. In the paper "Panel Data Models with Spatially Correlated Error Components," published in the *Journal of Econometrics* in 2007, Ingmar Prucha, jointly with Mudit Kapoor and Harry Kelejian, considers GMM estimators for a panel model where the errors may consist of a spatially autocorrelated term. The GMM estimator for the spatial correlation parameters is based on quadratic moments

of the error process, taking into account the specific form of spatial correlation in the errors. Building on earlier work, the paper proposes a feasible spatial GLS estimator that uses efficient weighting constructed from a parametric estimate of the error covariance matrix. In joint work with Guido Kuersteiner, Ingmar Prucha provided the foundations for the asymptotic analysis of panel models with spatial dependence. The paper "Limit Theory for Panel Data Models with Cross-Section Dependence and Sequential Exogeneity" published in the *Journal of Econometrics* in 2013 develops a central limit theorem that can accommodate sequentially exogenous covariates and unobserved factor structures in settings applicable to cross-sectionally correlated panel data and spatial panel data models. In subsequent work, "Dynamic Spatial Panel Models: Networks, Common Shocks, and Sequential Exogeneity" (CES ifo Working Paper 5445), these authors extended their limit theory to analyze GMM estimators for Cliff–Ord-type panel models with spatial weight matrices for the endogenous variables and error terms. Their GMM estimators use both linear and quadratic moment conditions in a similar way as earlier work by Ingmar Prucha, but allow for sequentially exogenous covariates, and data dependent and even endogenously generated weight matrices. The paper also extends earlier work of Ingmar Prucha on linear–quadratic central limit theorems to allow for stochastic weight matrices. The latter further complicates the form of the limiting distribution. The paper provides a list of sufficient restrictions to eliminate serial correlation as well as correlation between linear and quadratic terms. These restrictions offer important simplifications essential for the feasible implementation of linear–quadratic GMM estimators. In joint work with Nazgul Jenish, Ingmar Prucha made important contributions to stochastic limit theory for spatial processes. In the paper "Central limit theorems and uniform laws of large numbers for arrays of random fields" published in the *Journal of Econometrics* , they prove uniform weak laws of large numbers and central limit theorems for spatially mixing processes. In a follow-up paper "On spatial processes and asymptotic inference under near-epoch dependence" published in the *Journal of Econometrics* in 2012, they prove laws of large numbers for spatially near-epoch-dependent processes. These results constitute an important extension over work by Bolthausen for spatially mixing processes because near-epoch dependence is a concept that is easier to verify in specific applications and in particular applies, unlike mixing, to infinite transformations that appear in models with spatial dynamics. In addition to handling spatial dependence in a flexible way, the approach also allows for general forms of heterogeneity, which is of great importance in cross-sectional data but which is often not allowed for in the spatial literature. The paper thus provides an important building block toward a more generally applicable theory of inference for spatial models.

In addition to fundamental theoretical contributions to the spatial literature, Ingmar Prucha also greatly contributed to the practical implementation of estimation methods for spatial models. In close collaboration with David Drukker and the Stata corporation, he produced a number of computational algorithms that implement his estimators. He also coauthored numerous papers with David Drukker that focus on the implementation and application of these procedures using the statistical software Stata. The collaboration with Stata was recognized to be an important advancement of the field and received funding from NIH. Ingmar Prucha is not only committed to the theoretical advancement of spatial econometrics but has also, through his col-

laboration with Stata in developing end user software, contributed enormously to the advancement of the field in terms of its practical applicability.

Ingmar Prucha's work on simultaneous equation models dates back to the very beginning of his academic career with an *Econometrica* publication on seemingly unrelated regression models with error components and a joint paper with Harry Kelejian, also published in *Econometrica*, on the estimation of simultaneous equation models with nonnormal error distributions. Around the same time, he also published a paper on maximum likelihood estimation and instrumental variables estimation of simultaneous equation systems with error components in the *International Economic Review*, which at the time was a top journal in economics. Inference in simultaneous equation models continues to be an active area of research for Ingmar Prucha. In the paper "Estimation of simultaneous systems of spatially interrelated cross sectional equations," published in the *Journal of Econometrics* in 2004 and joint with Harry Kelejian, the concept of simultaneous equations is for the first time considered formally in spatial models. The authors extend their GMM instrumental variables estimation methods for spatial models to the context of simultaneous equation models. Ingmar Prucha's current research continues to include work on simultaneous questions models which, as an example, have important applications in areas where individuals decide simultaneously on multiple activities affected by interactions with peers.

Before mainly working on spatial models, Ingmar Prucha made important contributions to the estimation theory for nonlinear dynamic models. Ingmar Prucha, jointly with Benedikt Pötscher, was invited to write a review article on asymptotic theory for nonlinear dynamic models for *Econometric Reviews.* Rather than writing a review article, they wrote two papers that provided a new encompassing theory of asymptotic inference in this class of models, and covering many of the competing existing approaches. The two papers became the foundation for their state-of-the art monograph "Dynamic nonlinear econometric models: Asymptotic theory" which appeared in Springer Verlag in 1997. This text remains to this date one of the most important resources for results on nonlinear models fitted to dependent and heterogeneous data. The book most notably provides a comprehensive overview over L_p approximation concepts and near-epoch dependence and preservation of these concepts under nonlinear transformations. The latter is a critical component in proofs of asymptotic approximations in nonlinear models with dependence. The authors also cover uniform laws of large numbers, a topic they contributed to in a series of papers including their *Econometrica* paper published in 1989. Uniform laws of large numbers are key ingredients in every proof of asymptotic approximations for nonlinear econometric models. The work of Ingmar Prucha and Benedikt Pötscher significantly contributed to our understanding of such uniform laws. Their results are applicable to generic classes of estimators under assumptions of temporally dependent and heterogeneous data as well as time-varying criterion functions. At the heart of their argument lies a technique that translates pointwise laws of large numbers on dense subsets of totally bounded parameter spaces into uniform laws with an approximation technique that is based on the Ascoli–Arzela theorem.

Early in his career, Ingmar Prucha's research focused on empirical work examining the determinants of physical capital investment and R&D expenditures leading to numerous publications in this area over the years. A highly cited paper is "Estimation

of the depreciation rate of Physical and R&D Capital in the U.S. total Manufacturing Sector," joint with Ishaq Nadiri and published in *Economic Inquiry* in 1996. This paper proposes a model for the depreciation rate of physical and R&D capital in the USA. Empirical estimates of these parameters are lower than the previous literature but higher than the estimate of the NBER at the time. Depreciation rates are important components in estimates of capital stocks, and this paper had a significant impact on how these stocks are being computed.

4 Personal remarks

4.1 Guido Kuersteiner, University of Maryland

I met Ingmar Prucha for the first time when I presented a paper on panel bias correction and instrumental variables estimation at the University of Maryland in 2001. While it would still take a number of years until Ingmar and I started to collaborate on joint work, it was probably at the time of my visit when a bond between us started to form. Our bond was rooted in our joint research interests in econometrics, our dedication to the field, a strong belief in work that meets the highest standards of mathematical rigor and maybe a common cultural heritage. Sometime in 2008, Ingmar suggested that we work on a joint paper that aimed at developing a central limit theorem applicable to panel data with cross-sectional dependence. I was immediately enthusiastic about the idea and very happy to agree to the collaboration. Our work took us further than we had originally imagined, leading to a paper that explored stable convergence of random sequences, a concept that was, and still is, relatively unknown in econometrics. Out of our first joint paper which was published in the *Journal of Econometrics* in 2013, we embarked on a new research agenda, now more narrowly focusing on spatial econometrics. I consider myself very fortunate that Ingmar generously engaged me in his own research on spatial models. Equipped with the limit theory, we developed in our first project we were able to address difficult issues related to the estimation of models where networks are formed endogenously. In line with Ingmar's research philosophy, we focus on GMM estimation which leads to estimators that are significantly more tractable than corresponding likelihood-based methods. Clearly, this work would not have been possible without Ingmar's extensive experience in the area of spatial econometrics.

Collaboration with others, in most cases, is a very rewarding and stimulating activity. This is particularly true in Ingmar's case. I feel extremely blessed to have him as a coauthor and friend. It is no exaggeration that I learned enormously from our joint work and that I became a better academic as a result of it. His attention to detail, precision in execution of proofs and accuracy of argumentation set a standard that only few are able to adhere to.

In 2013, I was lucky enough to have the opportunity to join the economics department at Maryland. Clearly, Ingmar was instrumental in giving me this opportunity. I now was fortunate enough not only to have Ingmar as a coauthor but also as a faculty colleague. We are coteaching two graduate courses and are closely collaborating in advising a number of graduate students. Ingmar is extremely supportive of the

economics department in general and the econometrics group in particular. He is a dedicated teacher and mentor to his students with a long track record of producing successful students specializing in applied and theoretical work in spatial econometrics. I witnessed first hand how helpful and supportive he is of the graduate students who work with him and under his supervision.

Despite his enormous mathematical skills and extreme knowledge of his research field, Ingmar always remained modest about himself. I came to appreciate Ingmar as someone with an enormously steady moral compass and the highest ethical and professional standards. He is a true role model I will always try to live up to.

4.2 John Chao, University of Maryland

I am very fortunate to have had Ingmar Prucha as my colleague and mentor since 1995 when I joined the Economics Department at the University of Maryland as an assistant professor. From the very outset, Ingmar was a very helpful and supportive senior colleague. To help lessen the burden of my graduate course preparation, Ingmar generously shared with me his lecture notes, syllabi, problem sets, and other course material. Ingmar's econometrics lecture notes are exemplary in terms of their clarity and thoroughness, and also in terms of the mathematical rigor with which the main results are stated and proven. As I got to know Ingmar better, I come to realize that clarity of thought, thoroughness, and an insistence on the highest academic standard and rigor are words that describe Ingmar more generally, not just the lecture notes he put together. I have learned a great deal from reading his lecture notes, and I try to follow the examples he has set. Even today, I try my best to teach classes at Maryland in a way that emulates the high standards which Ingmar has for his classes.

It was around the time that I joined the department at Maryland that Ingmar and Harry Kelejian started their exciting and pathbreaking research program on spatial econometrics. This work has now continued with Ingmar's ongoing collaboration with another of my colleagues, Guido Kuersteiner. With these collaborators, Ingmar has written an impressive sequence of papers on spatial econometrics that has not only provided fundamental theoretical results but has also led to the development of an extensive toolkit for empirical researchers wanting to apply spatial models. While I myself have never worked directly in this area, I was nevertheless influenced in my own research by the work that Ingmar has done in spatial econometrics. To give but one example, in 2001, Ingmar published with Harry a well-known paper in the *Journal of Econometrics* on the asymptotic distribution of the Moran I statistic for testing spatial correlation. An important technical result of the paper is a central limit theorem for linear–quadratic forms. At the time, I was trying to derive the asymptotic distribution of Jackknife instrumental variables (JIV) estimators in nonstandard settings with many weak instruments and error heteroskedasticity. Reading Ingmar's 2001 paper allowed me to realize that the result I was trying to obtain also required showing a central limit theorem for bilinear forms with a martingale difference structure. Although the conditions that had to be imposed to obtain asymptotic normality of the JIV estimators under many weak instruments turned out to be different from the conditions that Ingmar and Harry assumed on the spatial weighting matrix appearing in the Moran I

test statistic, what I learned from reading Ingmar's 2001 paper was nonetheless very helpful in pointing me in the right direction.

Ingmar has contributed to the Maryland economics department in many immeasurable ways that go much beyond his teaching and scholarship. He has held a number of important leadership positions within our department including being the current chair of our senior recruiting committee, and also having served as the chair of this committee several times in the past. In his administrative and leadership roles, Ingmar is always fair and even-handed; over the years, I have witnessed him handling many difficult situations, always with wisdom and integrity. To younger colleagues and graduate students, he is much more than a mentor and advisor; he is an irreplaceable father figure, who truly cares about their welfare. I have personally benefited from the many sound advice that he has given me. The Ingmar that I know is not only an outstanding scholar but a great person as well.

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