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Dynamic modeling in economics: growth and sustainability

Giorgio Fabbri

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UNIVERSITÉ DE GRENOBLE-ALPES

Mémoire pour l'obtention de l'**Habilitation à Diriger des
Recherches** en Sciences Economiques

présenté et soutenu par

Giorgio Fabbri, Chargé de Recherche au CNRS, Section 37

le 30 novembre 2020

*Dynamic modeling in economics:
growth and sustainability*

Membres du jury :

<i>Président :</i>	Thomas SEEGMULLER	- CNRS and AMSE
<i>Rapporteurs :</i>	Katheline SCHUBERT	- PSE et Univ. Paris 1
	Vladimir VELIOV	- Vienna University of Technology
	Anastasios XEPAPADEAS	- Univ. of Bologna and Athens Univ. of Econ. and Business
<i>Examineurs :</i>	Stefano Bosi BOSI	- Univ. d'Evry-Val d'Essonne
	Hippolyte D'ALBIS	- CNRS and PSE

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It is now starting to be a few years that I am doing the work of a researcher and I have many debts to people who have given me confidence and who have helped me to grow.

Even at the risk of forgetting someone I would like to try to thank some of them: Andrzej Swiech who welcomed me and put up with me in Atlanta for almost a semester back in 2005 (my first real research stay abroad), Silvia Faggian with whom I wrote some of my first articles (it's a real thank because I was writing in a really embarrassing way at the time), Benjamin Goldys who gave me the chance to give a peek at the world of financial mathematics for a year in Sydney.

All the people with whom I was lucky enough to work and with whom I have developed over the years, without exception, a true friendship that lasts over time: (in addition to those already mentioned) Emmanuelle Augeraud-Véron, Mauro Bambi, Carmen Camacho, Tom Dedeurwaedere, Salvatore Federico, Michele Di Maio, Vincenzo Lombardo, Paolo Malined-Ghidi, Patrick Pintus, Francesco Russo.

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I thank Stefano Bosi who had the courage to help me to come to France when I could hardly say “je m'appelle Giorgio”; Karine Gente, Carine Nourry, Thomas Seegmuller, Alain Venditti who welcomed me with great warmth in Marseille, Patrick Criqui, Stéphane Lemarié, Stéphane Robin and all colleagues from the GAEL laboratory in Grenoble as well as, of course, the administrators, starting with Gwenaëlle Clément et Céline Rival, who put up with me when I mess up, that is very often.

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Contents

1 Curriculum Vitae	7
1.1 Personal informations	7
1.2 Education and positions	8
1.2.1 Other	8
1.3 Study/research periods in other universities (four weeks or more)	8
1.4 Administrative and collective responsibilities	9
1.5 Organization of conference and workshop	9
1.6 Talks and seminars	10
1.7 Participation in research projects	10
1.7.1 Head/direction of projects	10
1.7.2 Personal fundings	10
1.7.3 Participant/member of projects	11
1.8 Didactics	12
1.8.1 Referee for Ph.D. thesis	12
1.8.2 Supervisor of master degrees	12
1.8.3 Courses	12
1.9 Referee activity	13
1.10 Publications	14
1.10.1 Books	14
1.10.2 Papers in peer-reviewed journals	14
1.10.3 Papers in collections	17
2 Past scientific activities	19
2.1 Growth Dynamics	19
2.1.1 Dynamics of capital accumulation, obsolescence and in- vestment in vintage capital models	19
2.1.2 Growth and Population: The Problem of Optimal Size . .	23
2.1.3 The Spatial Dimension in Growth Patterns	26
2.1.4 Financial market integration and growth	29
2.2 Topics in environmental economics	30
2.2.1 Exploitation of renewable resources: the case of forests .	30
2.2.2 Environmental brokers and agri-environment measure . .	32
2.2.3 The insurance value of biodiversity in a dynamic context	33
2.3 Other works	35
2.3.1 Optimal control and Hamilton-Jacobi-Bellman equation .	35
2.3.2 Development Economics	37

3	Ongoing research and future perspectives	39
3.1	Strategic exploitation of resources with spatial dynamics	39
3.2	Strategic interaction and transboundary pollution	44
3.3	Climate Change and Economic Decision Making	49
3.4	Covid-19	50
	Bibliography	59

Curriculum Vitae

Contents

1.1	Personal informations	7
1.2	Education and positions	8
1.2.1	Other	8
1.3	Study/research periods in other universities (four weeks or more)	8
1.4	Administrative and collective responsibilities	9
1.5	Organization of conference and workshop	9
1.6	Talks and seminars	10
1.7	Participation in research projects	10
1.7.1	Head/direction of projects	10
1.7.2	Personal fundings	10
1.7.3	Participant/member of projects	11
1.8	Didactics	12
1.8.1	Referee for Ph.D. thesis	12
1.8.2	Supervisor of master degrees	12
1.8.3	Courses	12
1.9	Referee activity	13
1.10	Publications	14
1.10.1	Books	14
1.10.2	Papers in peer-reviewed journals	14
1.10.3	Papers in collections	17

1.1 Personal informations

Born April 10, 1979 in Cesena (Italy)

Nationalities French (since the 31st of March 2019) and Italian

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1.2 Education and positions

Oct 15 - Today Chargé de Recherche, CNRS, France

Oct 15 - Aug 17 Assigned to laboratory: AMSE, Marseille, France

Sept 17 - Today Assigned to laboratory: GAEL, Grenoble, France

Sep 12 - Aug 15 PRAS (PROfesseur ASSocié) Univ. Evry - Val d'Essonne, France

Nov 08 - Aug 12 Assistant professor University "Parthenope", Naples, Italy.

Jan 06 - Oct 08 Research fellow University "Luiss - Guido Carli", Rome, Italy

Jan 07 - Jan 08 Research associate (post-doc) Univ. of NSW, Sydney, Australia

Nov 02 - Oct 06 PhD student University "La Sapienza", Rome, Italy.

Oct 98 - Jul 02 Student Scuola Normale Superiore, Pisa, Italy

1.2.1 Other

Dec 09 - Today Extramural fellow IRES, Univ. Cat. de Louvain, Belgium

Aug 17 - Today Fellow Global Labor Organization (GLO)

1.3 Study/research periods in other universities (four weeks or more)

Georgia Institute of Technology (Gatech) GA. USA.

Université Paris I Panthéon-Sorbonne. France.

Université catholique de Louvain. Belgium.

Ecole Nationale Supérieure de Techniques Avancées (ENSTA). Paris, France.

Istanbul Bilgi University. Turkey.

University of Pisa. Italy.

Aix-Marseille School of Economics, Université Aix-Marseille. France.

Luiss - Guido Carli, Rome. Italy

1.4 Administrative and collective responsibilities

2011 - Today Member of the **Ph.D. committee** of the Ph.D. in *Economics, management and accounting* of the University of Naples *Parthenope*

2012 - 2015 Member of the **scientific committee of the Labex MME-DII** *Modèles Mathématiques et Économiques de la Dynamique, de l' Incertitude et des Interactions*.

2012 - 2015 Member of the **board of the laboratory EPEE** , University Evry-Val d'Essonne (2012-2015).

1.5 Organization of conference and workshop

2021 (Co)organizer of the **FAERE 2021 conference** (French Association of Environmental and Resource Economists) in Grenoble

2020 (Co)organizer of the **Online FAERE 2020 conference** (French Association of Environmental and Resource Economists).

2018 (Co)organizer of the session **PDE Constrained Optimization in Economics** an the *14th Viennese Conference on Optimal Control and Dynamic Games* Vienna, July 3-6, 2018.

2018 (Co)organizer of the session **Infinite dimensional stochastic modeling in economics and finance** an the *14th Viennese Conference on Optimal Control and Dynamic Games* Vienna, July 3-6, 2018.

2014 (Co)organizer of the Workshop **Dynamic models for endogenous population**. Paris, 5 February 2014.

2014 (Co)organizer of the Workshop **Network Dynamics and Public Goods** Paris, 24 January 2014.

2014 (Co)organizer of the Workshop **Advances in dynamic interations** Paris, 16 January 2014.

2014 (Co)organizer of the Workshop **Finance in General Equilibrium** Paris, 10 January 2014.

2013 (Co)organizer of the **Conference DIET** (Dynamic Interaction Economic Theory) Paris, 16 et 17 December 2013.

2012 (Co)organizer of the **Journée dynamique** workshop. Evry, France. 8 November 2012

1.6 Talks and seminars

More than 40 talks in conference and workshops (Vienna, Seattle, Heidelberg, Algiers, Paris, Paris, Lyon, Rennes, Evry, Milan, Pisa, Rethymno, Thessaloniki, Catania, Lisbon, Parma, Moscow, Lecce, Marseille, Sydney, Trieste, Turin, Cachan, Nanterre, Florence, Faro), **more than 20 on invitation**

More than 20 invited seminars in Departments and research groups (Bologna, Lyon, Rome, Paris, Marseille, Grenoble, Cergy, Istanbul, Venice, Rio de Janeiro, Sydney, Evry, Lille).

1.7 Participation in national and international research projects

1.7.1 Head/direction of projects

2020-2021 Head of a project *Initiatives de Recherche Stratégiques (IRS) - IDEX Université Grenoble Alpes*. Title *Intermediaries, endogenous evolution of preferences, ecological transition*

2019-2020 Head of a project *Initiatives de Recherche Stratégiques (IRS) - IDEX Université Grenoble Alpes*. Title *The spatial strategic game of trans-boundary pollution dynamics and the local efficiency hypothesis*

2018-2019 Head of a project *Initiatives de Recherche Stratégiques (IRS) - IDEX Université Grenoble Alpes*. Title *Strategic behaviour and regulation in the management of common goods distributed in space: the case of fisheries resources*.

2013, renewed in 2014 Head of a project *PEPS HuMaIn 2013 - CNRS*. Title *L'économie de la biodiversité dans un modèle de culture optimal*.

2013-2014 (Co)responsible of the Semester thematic SHADE (Strategic/Heterogeneous Agent in Dynamic Economies), financed by the LABEX MME-DII. Paris - Evry September 2013 - February 2014.

1.7.2 Personal fundings

2019-2020 Projet “exploratoire” *Dynamic strategic interaction in regional air polluting economic activities with spatial externalities* financed by the Labex MME-DII

2015 Financing of the city of Marseille for installation *Allocation Chercheurs 2015-2016*

2014-2015 *Délégation - Labex MME-DII*: funding to finance a reduction in

my teaching time to complete the book *Stochastic Optimal Control in Infinite Dimensions*

2014 Personal grant of the Université of Evry-Val d'Essonne *Fonds pour le Rayonnement de la Recherch*. Title of the project *Hétérogénéité des entrepreneurs, qualité du gouvernement et efficacité de la politique industrielle*.

2012, renewed in 2013 Personal grant *Unicredit's Post-Doc Research Grant*. Title: *International borrowing without commitment: volatility of capital inflow and welfare*.

1998 - 2002 Scholarship at the Scuola Normale Superiore (Pisa, Italy)

1.7.3 Participant/member of projects

2016-2017 Participant of the project *Network Connections in Peer-to-Peer Lending* funded by a grants of the *Institute Europlace de Finance - LABEX Louis Bachelier*, France. Head: Ester Faia.

2012-2018 Participant of the project *Heterogeneity, Dualism and Growth* funded by the *Legge 5 - Regione Campania (Italy)*. Head: Michele Di Maio.

2015-2018 Member of the Labex AMSE - *Aix-Marseille School of Economics*. Head: Alain Trannoy

2012 - today Member of the Labex MME-DII - *Modèles Mathématiques et Économiques de la Dynamique, de l'Incertitude et des Interactions*. Head: Arnaud Lefranc and Ani Guerdjikova

2013-2015 Participant of the project *Evolution differential problems: deterministic and stochastic approaches and their interactions*, funded by an italian grant *PRIN* (PRIN, "Programmi di Ricerca di Interesse Nazionale", are national research projects funded by italian ministry of university). Head: Marco Furhman.

2009-2012 Participant of the project *Control of Partial Differential Equations*, GDRE - *Groupement De Recherche Europeenne Italo-French* [INdAM-CNRS]. Head: Piermarco Cannarsa.

2010-2011 Participant of the project *Deterministic and stochastic methods in studying evolution problems*, funded by an italian grant *PRIN* (2008). Head: Alessandra Lunardi.

2007-2008 Participant of the project *Optimization and control methods for the management of public debt; static and dynamics models*, funded by an italian grant *PRIN* (2006). Head: Fausto Gozzi.

2005-2011 Member of the Group GNAMPA *National group for mathematical analysis, probability and their applications - INdAM National institute of high mathematics*.

1.8 Didactics

1.8.1 Referee for Ph.D. thesis

- **Infinite horizon optimal control problems with non-compact control space. Existence results and dynamic programming.** Ph.D. in Mathematics, University of Pise (Italy). Francesco BARTALONI, 2019/2020.
- **Four essays in economic development and finance.** PhD in Economics and Finance, University *Tor Vergata*, Rome (Italy). Enrico LUPI. 2018/2019.

1.8.2 Supervisor of master degrees

- **Competition, credit constraint, and growth.** Master M1 (Master *Advanced Economics* de l'ENS Lyon). Juliette COLY, 2018/2019.
- **Arbitrage Pricing for Financial Derivatives in Continuous Time.** Master (Mémoire de master M1 mention *Finance*). Jean-Claude HOUEDJISSIN Université d'Evry - Val d'Essonne, 2014/2015.
- **Arbitrage and martingale measure in financial markets.** Master (Mémoire de master M1 mention *Finance*). Quang Tùng TÔ. Université d'Evry - Val d'Essonne, 2014/2015
- **Arbitrage Pricing for Financial Derivatives in Continuous Time.** Master (Mémoire de master M1 mention *Finance*). Naom ARON, Mamadou Bhoie BAH. Université d'Evry - Val d'Essonne, 2013/2014
- **Modélisation des risques de Marché : la Value at Risk.** Master (Mémoire de master M1 mention *Finance*). Yul-Elkin WONG-GAR-HENG. Université d'Evry - Val d'Essonne, 2013/2014

1.8.3 Courses

- **Macroeconomics 2 (open macroeconomics)** - M1 (english). Ecole Normale Supérieure de Lyon. 2018/2019, 2019/2020
- **Stochastic processes and applications to finance** - M2 (french). Université d'Evry - Val d'Essonne. 2014/2015
- **Economy of asset pricing** - M1 (french and english). Université d'Evry - Val d'Essonne. 2014/2015, 2014/2014
- **Macroeconomics** - L3 (french). Université d'Evry - Val d'Essonne. 2014/2015, 2013/2014, 2012/2013
- **Teaching assistant (TD) for a course in Growth Theory** - L2 (french). Université d'Evry - Val d'Essonne. 2014/2015
- **Teaching assistant (TD) for a course in Microeconomics** - L1 (french). Université d'Evry - Val d'Essonne. 2013/2014, 2012/2013

- **Mathematical methods** - L1 (french). Université d'Evry - Val d'Essonne. 2013/2014
- **Microeconomics and games** - M1 (english). Vietnam National University, Ho Chi Minh city, Vietnam. 2012/2013
- **Half of a course in "Macroeconomics"** - M1 (french). Université d'Evry - Val d'Essonne. 2012/2013
- **Statistics** - L2 (Cours/TD) (french). Université d'Evry - Val d'Essonne. 2012/2013
- **Institutions of political economy** (italian). University of Naples *Parthenope*. 2011/2012
- **A third of a course in "Microeconomics"** (italian). University of Naples *Parthenope*. 2011/2012
- **Growth theory** (italian). University of Naples *Parthenope*. 2009/2010
- **Topics in optimal control theory** (italian). Short course to Ph.D. students at University of Naples *Parthenope*. 2008/2009
- **Development economics** (italian). University of Naples *Parthenope*. 2008/2009
- **Teaching assistant for "Pre-course in quantitative methods"** (english). LUISS - G.Carli, Rome. 2008/2009

1.9 Referee activity

Referee for: Journal of Economic Theory, Journal of European Economic Association, American Journal of Agricultural Economics, Economic Theory, Journal of Economic Dynamics and Control, Journal of Mathematical Economics, Journal of Population Economics, Revue Économique, Southern Economic Journal, Economic Letters, Mathematical Social Sciences, Journal of Public Economic Theory, B.E. Journal of Theoretical Economics, Research in Economics, Mathematical Population Studies, Journal of Mathematics and Mathematical Sciences, Natural Resource Modeling, Journal of Mathematical Analysis and Applications, Stochastic Processes and their Applications, SIAM journal on Control and Optimization, ESAIM: Control, Optimization and Calculus of Variations, Journal of Evolution Equations, Journal of Applied Probability/Advances in Applied Probability, Journal of Optimization Theory and Applications, Annals of Operations Research, Nonlinear Analysis Series B: Real world applications, Reviewer for Mathematical Reviews (Mathscinet).

1.10 Publications

1.10.1 Books

- B1) G. Fabbri, F. Gozzi and A. Świeżh Stochastic Optimal Control in Infinite Dimensions: Dynamic Programming and HJB Equations. *Probability Theory and Stochastic Modelling*, vol. 82, XXIV+916 pages, Springer, Berlin. (The whole book is written by Fabbri, Gozzi and Świeżh, with the exception of Chapter 6 that is a contribution of M. Fuhrman and G. Tessitore)

1.10.2 Papers in peer-reviewed journals

- A1) P. Melindi Ghidi, T. Dedeurwaerdere, G.Fabbri Using Environmental Knowledge Brokers to Promote Deep Green Agri-environment Measures. **Ecological Economics**, to appear.
- A2) G. Fabbri, S. Faggiian and G. Freni Policy effectiveness in spatial resource wars: a two-region model. **Journal of Economic Dynamics and Control**, 111, article 103818, 2020.
- A3) R. Boucekkine, G. Fabbri, F. Gozzi and S. Federico. From firm to global-level pollution control: the case of transboundary pollution. To appear in **European Journal of Operation Research**
- A4) R. Boucekkine, G. Fabbri, F. Gozzi and S. Federico. Optimal Economic Growth Through Capital Accumulation in a Spatially Heterogeneous Environment. **Journal of Economic Geography**, 19(4): 1287-1318, 2019.
- A5) E. Augeraud-Veron, G. Fabbri and K. Schubert The value of biodiversity as an insurance device. **American Journal of Agricultural Economics**, 101(4):1068–1081, 2019.
- A6) R. Boucekkine, G. Fabbri, F. Gozzi and S. Federico. Geographic Environmental Kuznets Curves: the optimal growth linear-quadratic case. **Mathematical Modelling of Natural Phenomena**, 14(1):105, 2019.
- A7) R. Boucekkine, G. Fabbri, and P. Pintus. Short-run pain, long-run gain: the conditional welfare gains from international financial integration. **Economic Theory**, 65(2):329-360, 2018.

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- A8) G. Fabbri, and F. Russo. HJB equations in infinite dimension and optimal control of stochastic evolution equations via generalized Fukushima decomposition **SIAM journal on Control and Optimization**, 55-6 (2017):4072-4091, 2017.
- A9) G. Fabbri, S. Faggian, G. Freni Non-existence of optimal programs for undiscounted growth models in continuous time. **Economics Letters**, 152:57-61, 2017.
- A10) G. Fabbri International borrowing without commitment and informational lags: choice under uncertainty. **Journal of Mathematical Economics**, 68:103-114, 2017.
- A11) G. Fabbri and F. Russo Infinite dimensional weak Dirichlet processes and convolution type processes **Stochastic Processes and their Applications**, 127(1):325-357, 2017.
- A12) G. Fabbri Ecological Barriers and Convergence: a Note on Geometry in Spatial Growth Models. **Journal of Economic Theory**, 162:114-136, 2016.
- A13) G. Fabbri, S. Faggian, G. Freni On the Mitra-Wan model of forestry management in continuous time. **Journal of Economic Theory**, 157:1001-1040, 2015.
- A14) R. Boucekkine, G. Fabbri, and F. Gozzi. Egalitarianism under population change: age structure does matter. **Journal of Mathematical Economics**, 55(1):86–100, 2014
- A15) G. Fabbri, S. Federico. On the Infinite-Dimensional Representation of Stochastic Controlled Systems with Delayed Control in the Diffusion Term. **Mathematical Economics Letter**, 2(3-4):33–43, 2014.
- A16) C. Di Girolami, G. Fabbri and F. Russo. The covariation for Banach space valued processes and applications. **Metrika**, 77(1):51–104, 2014.
- A17) R. Boucekkine, G. Fabbri, and P. Pintus. Growth and financial liberalization under capital collateral constraints: The striking case of the stochastic AK model with CARA preferences. **Economics Letters**, 122(2):303–307, 2014.
- A18) R. Boucekkine, C. Camacho, and G. Fabbri. On the optimal control of some parabolic differential equations arising in economics **Serdica**

- Mathematical Journal**, special issue in honor of Vladimir Veliov, 39(3-4):331–354, 2013.
- A19) R. Boucekkine, C. Camacho, and G. Fabbri. Spatial dynamics and convergence: The spatial AK model. **Journal of Economic Theory**, 148(6):2719–2736, 2013.
- A20) M. Di Maio and G. Fabbri. Product boycott, household heterogeneity and child labor. **Journal of Population Economics**, 26(4):1609–1630, 2013.
- A21) R. Boucekkine and G. Fabbri. Assessing parfit’s *Repugnant Conclusion* within a canonical endogenous growth set-up. **Journal of Population Economics**, 26(2):761–767, 2013.
- A22) R. Boucekkine, G. Fabbri, and P. Pintus. On the optimal control of a linear neutral differential equation arising in economics. **Optimal Control Applications and Methods**, 33(5):511–530, 2012.
- A23) M. Bambi, G. Fabbri, and F. Gozzi. Optimal policy and consumption smoothing effects in the time-to-build AK model. **Economic Theory**, 50(3):635–669, 2012.
- A24) R. Boucekkine, G. Fabbri, and F. Gozzi. Revisiting the optimal population size problem under endogenous growth: minimal utility level and finite life. **Asia-Pacific Journal of Accounting & Economics**, Special issue edited by Kazuo Nishimura, 18(3):287–306, 2011.
- A25) R. Boucekkine, G. Fabbri, and F. Gozzi. Maintenance and investment: Complements or substitutes? a reappraisal. **Journal of Economic Dynamics and Control**, 34(12):2420–2439, 2010.
- A26) G. Fabbri, F. Gozzi, and A. Swiech. Verification theorem and construction of ε -optimal controls for control of abstract evolution equations. **Journal of Convex Analysis**, 17(2):611–642, 2010.
- A27) G. Fabbri and B. Goldys. An LQ problem for the heat equation on the halfline with Dirichlet boundary control and noise. **SIAM Journal on Control and Optimization**, 48(3):1473–1488, 2009.
- A28) G. Fabbri and F. Gozzi. Solving optimal growth models with vintage capital: The dynamic programming approach. **Journal of Economic Theory**, 143(1):331–373, 2008.

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- A29) G. Fabbri. A Viscosity Solution Approach to the Infinite-Dimensional HJB Equation Related to a Boundary Control Problem in a Transport Equation. **SIAM Journal on Control and Optimization**, 47:1022–1052, 2008.
- A30) G. Fabbri. Viscosity Solutions to Delay Differential Equations in Demography. **Mathematical Population Studies**, 15(1):27–54, 2008.
- A31) G. Fabbri, F. Gozzi, and S. Faggian. On the dynamic programming approach to economic models governed by ddes. **Mathematical Population Studies**, 15(4):267–290, 2008.

1.10.3 Papers in collections

- C1) G. Fabbri. A dynamic programming approach in hilbert spaces for a family of applied delay optimal control problems. In R. Glowinski and J.P. Zolesio., editors, *Free and Moving Boundaries: Analysis, Simulation and Control*, volume 252 of *Lecture Notes in Pure and Applied Mathematics*, pages 375–394. 2007.

Themes and contributions of past scientific activities

Contents

2.1 Growth Dynamics	19
2.1.1 Dynamics of capital accumulation, obsolescence and investment in vintage capital models	19
2.1.2 Growth and Population: The Problem of Optimal Size	23
2.1.3 The Spatial Dimension in Growth Patterns	26
2.1.4 Financial market integration and growth	29
2.2 Topics in environmental economics	30
2.2.1 Exploitation of renewable resources: the case of forests	30
2.2.2 Environmental brokers and agri-environment measure	32
2.2.3 The insurance value of biodiversity in a dynamic context	33
2.3 Other works	35
2.3.1 Optimal control and Hamilton-Jacobi-Bellman equation	35
2.3.2 Development Economics	37

In these pages, I describe my past research activity by classifying it chronologically according to a few themes of interest. In order to make the text more compact, I will focus on the contributions I consider the most significant and will limit myself to mentioning the others.

2.1 Growth Dynamics

2.1.1 Dynamics of capital accumulation, obsolescence and investment in vintage capital models

Vintage capital models are models in which the stock of capital, at any point in time, is described as a heterogeneous set of different generations of machines. One of the intuitions behind this approach is the idea that technical progress

is *embodied* in capital goods: a new technology influences the production process only if new machines use that technology. This leads to distinguish generations of machines that are replaced over time, emphasizing the importance of stratification by age of capital.

Vintage capital modeling in macro-dynamic literature was first introduced by Johansen (1959) and Solow (1960) and it introduces a novelty with respect to the assumption of capital homogeneity used in the neoclassical growth paradigm, in which technological progress influences the productivity of all already installed capital (as, for instance, in the Solow-Swan model or the Ramsey-Cass-Koopmans model). It also brings a tractability problem because the dynamics of the models with explicit vintage structure depends at each moment on the entire composition of capital goods.

A long controversy on the relevance of the *embodiment hypothesis* in the 1960s opposed Solow (see especially Solow, 1960) and Jorgenson (e.g. Jorgenson, 1966). A series of empirical studies in the 1990s, including Gordon (1990) and Greenwood et al. (1997), definitively tipped the balance in favour of Solow's thesis by showing that embodiment is indeed the main channel through which technological progress influences productivity. These works were indeed one of the driving forces behind a new development in the literature on vintage/heterogeneous capital models which had a revival starting from the nineties. Following Boucekkine et al., 2011a we can attribute the causes of this renewed interest in vintage capital growth models to two other factors: the technical progresses in optima control theory and the burst of economic demography models with age structure of population.

My first contributions in the subject are contained in the paper Fabbri and Gozzi (2008) where we further study one of the reference models of the second-wave vintage capital growth model, notably the endogenous growth model with AK production function introduced by Boucekkine et al. (2005). We first show that it is possible to aggregate the different generations of capital goods present in the economy and to describe the dynamics of the system (also outside the *steady state*) using a single real variable, the *effective* capital. The fact of being able to aggregate (using suitable weights for different vintages) the various generations of capital is indeed very useful to being able to study the dynamics of the system.

All previous results of this type, starting with that of Solow (1960), concerned models with exponential capital depreciation, and thus models in which the lifetime of capital goods was potentially infinite (see, for example, Greenwood and Jovanovic, 2001). Our result is the first to treat a model with a fixed (and

finite) machine life.

A second result in Fabbri and Gozzi (2008) is the characterization of the depreciation function of each generation of capital goods. In a model where the life of capital goods is fixed (and known to agents) the value of an asset at the time of its destruction (or just before) must necessarily be zero. So its depreciation cannot be exponential, but it needs to satisfy a more complicated law. We are able to describe this law and, using it, the depreciation function of the aggregate capital stock which, in the model considered, constitutes the variable that determines the output.

We also refined the description of the dynamics of the system by giving a more precise characterization, compared to the previous results, of the short-term oscillations. They constitute, as already observed by Boucekkine et al (2005), one of the strengths of the model since it is able to reproduce, even in an AK model, the short-run oscillation dynamics between investment and the growth rate observed in the empirical data, and reconcile it with a strong positive correlation over the long run (see Jones 1995 and McGrattan 1998).

Vintage capital models provide an ideal context for analyzing depreciation and obsolescence phenomena. Indeed, since each capital good is considered with its own age, it is possible to represent more complicated and realistic depreciation dynamics than exponential dynamics *à la Jorgenson*. At the same time, the age of the different generations of capital influences the costs of the maintenance process, which are not at all negligible even though they are often absent in standard growth models. For example, the data on the Canadian economy presented by McGrattan and Schmitz (1999) show that, for their sample, maintenance costs amount to 50 per cent of investments in new capital goods.

To approach the problem one can draw inspiration from a classical idea introduced by Johansen (1959) about the lifetime of capital. He used a Leontief production function and he suggested that factor intensity is established at the time of the implantation of machines and that it remains constant over their lifetime (the so called *putty-clay assumption*). If this is the case, an increase in wages that accompanies the growth process, determines a finite lifetime for each element of the installed physical capital: each machine is eliminated when, because of the level of wages, it is no longer profitable¹.

In the paper Boucekkine, Fabbri and Gozzi (2010) we adapt this idea to the

¹This mechanism cannot be replicated under the *putty-putty assumption* used by Solow (1960) which uses a Cobb-Douglas production function, allowing a potentially infinite life of capital goods. A behavior similar to that of Johansen's model has been described in the model of Solow et al. (1966),

obsolescence problem and we endogenize the lifetime of machines by supposing that vintages are scrapped when, because of the cost of maintenance (which increases with the age of the machines), they are no longer profitable. The model distinguishes between the physical depreciation and obsolescence of assets and, solving it, we are able to characterize explicitly the relative value of vintages of different age and to find, in terms of the all vintage distribution, the optimal investment in new capital goods and its relative size with respect to maintenance costs.

We are also able to look at co-movements of maintenance costs and investments in new goods. Consistently with data from Licandro and Puch (2000), simulations on the model show a complementarity between repair costs and the acquisition costs of new goods.

The last contribution I mention on vintage capital model is the paper Bambi, Fabbri and Gozzi (2012). In this work we consider a model with *time-to-build*, i.e. a model which explicitly takes into account the time that elapses between the investment decision and the moment when the new generation of capital goods becomes productive.

A brief premise is necessary. While time-to-build models are not directly a sub-family of vintage capital models, it is clear that the two have an important feature in common (see also Benhabib and Rustichini, 1991): in both cases, past investments have different effects on capital and output depending on when they were made (and this difference is not limited to a few exponential-type depreciation effects). For this reason, an irregular pattern in the history of past investment implies shocks and an irregularity in the present capital stock also in time-to-build models.

The economic importance of time-to-build was already clear, for example, to Jevons (1871)², but the first study in which it is related to aggregate economic fluctuations is that of Kalecki (1935). Since then, many economists have worked on this theme: we mention for instance the fundamental work of Kydland and Prescott (1982), who show how, in a dynamic model with time-to-build, exogenous stochastic technological fluctuations could be amplified and constitute one of the determining factors of the economic cycle.

The time-to-build phenomenon is also well documented in the empirical literature, for example in the dataset of Koeva (2000) (obtained from a sample of companies in the Compustat database) the average time to install a facility is about two years and is not influenced by the business cycle in any significant way.

²See in particular the section “Capital is concerned with Time” in Chapter 7 of *Theory of capital*.

In Bambi, Fabbri and Gozzi (2012), a macro-dynamic model with exogenous and fixed time-to-build is studied. We do not consider shocks of an exogenous nature but the focus is on possible endogenous fluctuations.

We show that in the model (which has a linear production function and an iso-elastic utility) the representative agent (or the planner) implements at the optimum an exponential consumption strategy. To support this choice, oscillations in investment, and therefore in output, are necessary so in the model, agents implement at the optimum investments with strong fluctuations. A more detailed analysis of the mechanisms underlying the fluctuations and the *smoothing* of consumption shows that they depend on the profile of investments that have already been made but have not given rise to productive capital goods. The agents internalize the information on the future increase in production due to investments not yet active, and decides to anticipate part of the consumption by giving rise to smoothing. The anticipation phenomenon is more significant as the parameter that measures the time-to-built is major.

Other articles in which I have worked on vintage capital models (also from a methodological point of view) are : Fabbri (2008a, 2008b) and Fabbri et al. (2008).

2.1.2 Growth and Population: The Problem of Optimal Size

The choice to procreate is not only private and, even in the absence of coercive interventions, it is influenced by the public policies. Understanding the correct way to evaluate these policies is at the crossroads of the interests of the different fields of the human and social sciences. They are of course important in relation to the broader problem of the sustainability of human activities (see Arrow et al., 2004), in a context where population pressure is expected to continue to increase in the coming decades (World Population Prospects, 2019).

The problem of optimal population size in relation to social and economic organization was already of interest to Greek thinkers: the ideal city of Hippodamus is inhabited by 10,000 people, divided into three classes, whereas exactly 5040 persons (see Charbit, 1988) live in the utopian Platonic city³. Following Gottlieb (1945), we can consider Cannan (1914) and Wicksell (1913) as the economists which, departing from the still partially Malthusian approach of J. S. Mill and Marshall, inaugurated the modern literature on optimal population size.

³This choice has an “arithmetic” nature: it is chosen because 5040 has a lot of divisors - there are 60 of them.

Cannan and Wicksell considered the problem in the context of a stationary economics and determined the optimal population size by selecting the value that maximizes average consumption. The same average utility maximization criterion is used by some authors in dynamic context (see, for example, Part II of Pitchford, 1974). Edgworth (1925), in his review of Sidgwick's book *The elements of Politics*, called this criterion *Millian* (or *average utilitarianism*) and opposed it to a second possible approach that can be called *Benthamite* (or *total totalitarianism*) in which the optimal population size is determined so as to maximize the sum of all the utilities of the individuals living in the economy. Indeed, one of the first authors proposing a (static) model based on this second approach was Sidgwick; dynamic Benthamite models were developed later (see Dasgupta, 2005).

On the one hand there is a series of criticisms about the strongly anti-natalist tendency (see Dasgupta, 1969) or the dynamic inconsistency (see Hammond, 1988) of average utilitarianism. On the other hand, Edgworth (1925) had already detected a possible limitation of total utilitarianism, which became famous with Parfit (1984) as *repulsive conclusion*, consisting in privileging situations in which the population size is large, but consumption and income per capita are low.

The subsequent literature on optimal population size investigated several aspects of the problem. A number of contributions have been inspired by the Becker and Barro (1988, 1989) models with endogenous fertility, and are concerned with defining Paretian-type efficiency principles in nested generation models. Among these works, we can mention Golosov et al (2007), who present different notions of efficiency depending on the way the agents that have not yet been born are treated or Conde-Ruiz et al. (2010), who introduce the notion of *Millian efficiency*.

A second stream is more directly related to the literature generated by Parfit (1984). It is oriented towards the characterization and the study of the optimal trajectories of the system, once the optimal criterion to be considered has been established, see Nerlove et al. (1982, 1985), Palivos and Yip (1993) or Razin and Yuen (1995).

A last theme concerns the classification of social optimum criteria on the basis of a certain number of axioms (see for example Blackorby and Donaldson, 2005). In this reflection, the question, already underpinned by the discussion between Edgworth and Sidgwick, on the relationship between the criteria used and the consequent effects in terms of inequality (see also Atkinson, 2014) returns.

In Boucekkine and Fabbri (2013) we study under which conditions the

repugnant conclusion can be verified in an AK growth model with endogenous fertility. The population growth rate influences the growth rate of the economy via a “dilution term”. In contrast to previous contributions of the same type, notably Palivos and Yip (1993), a general dilution function, not necessarily linear, is considered. In fact, several studies (see, for example, Boucekkine et al., 2002, Blanchet, 1989 and Kelley and Schmidt, 1995) have already remarked, on the one hand, the theoretical limitations of the restriction to the linear case and, on the other hand, the non-linearity found in the empirical data. In our model we consider a family of social utility functions such as that of Palivos and Yip (1993), which admits, as extreme cases, average and total utilitarianism. We show that in the traditional linear dilution function model the *repugnant conclusion* never occurs for realistic values of the inter-temporal rate of substitution; conversely, it can occur when the growth rate of the population and that of the economy are linked by an U relationship, which is the empirical relationship found by Kelley and Schmidt (1995).

As already mentioned, there is an important link between the social optimum criteria used and the implications in terms of egalitarianism. The first authors to deal with this topic considered static economies, and thus could only question about intra-generational egalitarianism. Reformulating the problems of optimal population size in a dynamic framework, allows to raise questions about inter-generational egalitarianism.

In Boucekkine Fabbri and Gozzi (2014a) we investigated the importance of introducing the age-structure of the population for these questions. We look at the situation from the perspective of the accumulation of human capital so, in our approach, procreation and education are ways of transferring wealth from one generation to another. We use the family of social optimum functions already considered in Boucekkine and Fabbri (2013), a linear labour production function, and we take into account the costs related to procreation and child rearing.

The obtained results are rather surprising, and they reaffirm the idea of egalitarianism linked to a benthamian-type criterion. We first show, as a benchmark, that, independently of the possible different implications in terms of intra-generational inequalities, if the population structure is not taken into account (i.e. under a *perpetual youth* hypothesis), all the social optimum functions of the family prescribe the same level of consumption for all generations. This level is naturally different for each function and, as expected, it is higher for average utilitarianism, where the birth rate is minimal, and lower and lower as we approach to total utilitarianism, which, unsurprisingly, also corresponds to the higher level of fertility.

When the age structure of the population is taken into account, only total utilitarianism reproduces this egalitarian dynamic, while the other criteria provide for adjustments and transitional dynamics along which consumption levels of different generations are different.

Another paper in which I have worked on optimal population size models is Boucekkine Fabbri and Gozzi (2011) where we we make use of a minimum utility level *à la* Blackorby and Donaldson (1984).

2.1.3 The Spatial Dimension in Growth Patterns

The relationship between geographical characteristics, the location of economic activity and the process of development has always been a subject of interest to economists, already Smith (1776) was interested in the topic (see for instance the third chapter of the first book of the *Richness of Nations*). However, the effort to extend classical growth models to the spatial context is quite recent and the great wave of literature of *new economic geography* of the 1990s and early 2000s has focused mainly on phenomena such as the formation of cities and the causes (and consequences) of migration, using mostly discrete spatial models (often two-country models) with no capital accumulation processes.

As also pointed out by Desmet and Rossi-Hansberg (2010), when new economic geography models have taken into account the growth process, they have done so, most of the time, through a technical progress modeled *à la* Grossman-Helpman and without intertemporal optimization. They have therefore not produced spatial counterparts to canonical growth models such as those of Solow or Ramsey (see Fujita et al., 2001 and Fujita and Thisse, 2013⁴).

The first attempt to provide a Ramsey-Cass-Koopmans model including capital mobility and accumulation, is due to Brito (2004). In this contribution, production takes place in continuous time, at every point in space, and uses available capital *in loco*. By adapting an idea from classical economic geography (see for example Beckmann and Puu, 1985 and Isard et al., 1979) the author hypothesizes that capital tends to move from regions with greater capital intensity to regions with lower capital intensity. However, the model does not allow for the possibility that labor move.

⁴For instance, also in a more recent paper, Desmet and Rossi-Hansberg (2014) present a dynamic model in which technological progress, endogenous and localized in different points of a segment, guides the growth process (see also Desmet and Rossi-Hansberg, 2012). The model predicts neither the presence nor the accumulation of physical capital, and the production of manufacturing goods and services takes place through two factors: land and knowledge. Investment in R&D is made locally and, at equilibrium, is predominant in the most densely populated regions. Neither the agents nor the planner have rational anticipation.

After Brito (2004) a series of papers used variations of the same idea. In this stream we can cite the articles by Camacho et al. (2008), Brock and Xepapadeas (2008) and Boucekkine et al (2009), which, at least partially, offered methodological contributions and highlighted some technical difficulties emerging from the model proposed by Brito. Indeed, because of the spatial movements of capital, the dynamic optimization problem associated to the model is governed by a parabolic-type equation. In the mentioned articles, the authors found necessary conditions for optimality via a version of the Pontryagin maximum principle, but none of them gave a complete solution of the model. Some of them proposed simplifications to approach the problem: for example, Brito (2004) focuses on *travelling waves* type solutions, Boucekkine et al. (2009) focuses on the linear utility case and Brito (2011) studies the local dynamics of the system. In each of these works, the role of the spatial mobility of capital in the *steady state* is also highlighted. In fact, the *steady state* of a spatial growth model is characterized by a stationary configuration of capital in each locality, but it may include persistent trade activity between the different localities.

To overcome the technical difficulties described above, a number of authors, including Quah (2002) and Brock et al. (2014a, 2014b), used immobile factors of production (knowledge or capital), and modeled the interaction between different geographic regions through spatial externalities. This type of approach does not seem to be very consistent with the data of Comin et al. (2012) on the spatial propagation dynamics of technology, which seem rather to suggest the qualitative likelihood of the hypothesis used by Brito.

The article by Boucekkine, Camacho and Fabbri (2013a) is the first to explicitly solve a model of spatial growth with mobility and capital accumulation with a continuous spatial dimension⁵. The model described by Boucekkine, Camacho and Fabbri (2013a) is written, like others in the same stream, as an optimal control problem with a parabolic type equation and therefore presents some methodological difficulties. Unlike most of the previous studies, the chosen space support does not have a boundary. Indeed, the questions of convergence and divergence (in the sense of the economic growth theory) most often arise at the global level and the notion of boundary is not adapted to this context. In the model, individuals are distributed homogeneously and immobile in time, capital/wealth levels are initially heterogeneous, and production takes place at each point in space according to the capital present there. We have in this case an endogenous growth model. The chosen production function is a linear function of the capital (AK) with the same constant A in all spatial points.

⁵The article by Boucekkine, Camacho and Fabbri (2013b) presents methodological considerations on a slightly larger class of problems of the same type.

We find the solution that maximizes the social utility i.e. the optimal level of consumption at each point in space and at each moment. The optimal evolution of the spatial distribution of capital is determined implicitly. There are many forces at play: despite the tendency towards divergence which is intrinsic in endogenous growth models, the spatio-temporal dynamics of capital leads to a convergence over time of the (*detrended*) capital/wealth in the different points of space.

A further step is taken in Fabbri (2016), where the role of geographical structure in the growth process is taken into account. In fact, the “geographical dimension” and the development process interact through several mechanisms that can make growth unequal, for instance: climate differences, which impact the productivity of the land and human capital (this idea can already be found in Montesquieu and then in Marshall) or the geographical bias of technologies (see Sachs, 2001). In Fabbri (2016), taking up one of Diamond’s (1997) ideas, the emphasis is more on the notion of geography as morphology, i.e. the presence of natural barriers (mountains, oceans, ...) or natural infrastructures such as rivers or canals, which allow the circulation of capital, technology and ideas. A precursor in modeling of this idea is Quah (2002), but, as already remarked, in his analysis the only production factor used (knowledge) was immobile and exogenously generated. Thus, he did not have any accumulation process of the type traditionally used in growth models and, above all, he did not have the mobility of capital across space.

The analysis by Fabbri (2016) is carried out through a model which, in several aspects, is similar to that of Boucekkine, Camacho and Fabbri (2013a), but in which the geographical structure, instead of being described by a circle, is very general. In this way, we can highlight the impact of the morphological structure on the processes of convergence or divergence of wealth between different geographical areas. It emerges that the geographical structure is one of the determinants of the qualitative behavior of the economy. *Ceteris paribus* if we change the morphology, the qualitative behavior of the geographical distribution of capital changes over the long term, resulting both in convergence and divergence depending on the choice.

In the article Boucekkine, Fabbri, Federico and Gozzi (2019) we take up the analysis of Boucekkine, Camacho and Fabbri (2013a) by introducing the heterogeneity of productivity/technology in different locations and choosing an heterogeneous (exogenous) population distribution. The dynamics of capital does not converges anymore towards an homogeneous distributions. Indeed its distribution profile depends in this case on the relative strength of several forces at play: the *spatial technological discrepancy effect* which tends to

concentrate production in the most productive areas, the *inequality aversion effect* which comes from the concavity of the chosen utility function and push the consumption in different areas to equalize and the spatio-temporal dynamic of capital.

2.1.4 Financial market integration and growth

The problem of committing contracts is among the elements that limit access to credit in developing countries. An innovative way to model this state of affairs was proposed by Boucekkine and Pintus (2012), developing intuition of Coen and Sachs (1986). They assume that, since the borrowing country is unable to engage in an investment strategy, the creditor bases its decisions on past investments, and therefore on the historical evolution of wealth/capital of the country. The relationship between the measurement of the historical levels of the investments and the present borrowing capacity (and thus the possibility of new investments) is the basis of the *history effect* described by Boucekkine and Pintus (2012). This allows their model to reproduce a series of irregularities in the dynamics of macroeconomic variables, such as the *growth reversals*, which are recurrent and well-documented (see, for example, Jones and Olken, 2008 or Cuberes and Jerzmanowki, 2009) and to show their relationship with the past dynamics of the country's economy and with the process of financial integration.

In the paper Boucekkine, Fabbri and Pintus (2018) (with the companion technical paper Boucekkine Fabbri Pintus, 2012) we introduce in the framework of Boucekkine and Pintus (2012) explicit agent preferences so that we can endogenize savings choice (the original formulation Boucekkine and Pintus (2012) included an assumption *à la Solow* of fixed and exogenous savings propensity). Even in the new context the phenomenon of *growth reversals* can be reproduced and once again they depend on the past dynamics of the economy (*history effect*). In the new framework it is possible to study the welfare effects of the credit market opening. The analysis highlights two competing effects of the opening of the international credit market on the consumption dynamics of agents: the level of consumption decreases immediately after the opening, but its growth rate increases. In this sense, the model reproduces the qualitative dynamics that emerge from the empirical results obtained by Kaminsky and Schmler (2008).

The growth rate of the country in autarky (before opening the credit market) and its past capital accumulation dynamics determine which effect prevails. The framework is therefore quite rich: only countries whose economic structure allows a sufficiently high autarky growth rate have an interest in accessing

the international credit market. The model thus reproduces the idea that a minimum threshold of development is necessary for the opening of financial markets to be beneficial, in the spirit of the results of Edwards (2001) and Arteta et al. (2001).

The results obtained in Fabbri (2017) are also related to the this kind of questions. A stochastic version of the model of Boucekkine Fabbri and Pintus (2018) is presented⁶ We consider the volatility associated with the macroeconomic dynamics in autarky. It plays an important role especially in the context of a small country with an open (after the opening process) economy. This volatility may be due, for example, to productive specialization (Kraay and Ventura, 2007) or social conflicts (Raddatz, 2007). In Fabbri (2017) it is shown that the total strength of the history effect is not reduced by volatility; nevertheless, it can be seen that the relative weight of older events in determining the optimal choices of the planner decreases when the environment is more volatile (or in situations where individuals are more risk averse), and, conversely, recent events are more and more relevant in a context of high uncertainty.

The article Boucekkine, Fabbri and Pintus (2014) concerns the case of a small open economy with an AK production function. Uncertainty is associated with borrowing flows, and agents have CARA-type preferences (i.e., with constant absolute risk aversion). The model is able to isolate quite precisely the contribution to the given growth rate of the increase in savings (and thus investment) due to the risk associated with debt (*precautionary savings*). Through this channel, surprisingly enough, the growth rate of the economy declines when the volatility associated with the flow of loans tends to zero, and vanishes when the volatility is zero. The growth rate of the economy is also quite low when the volatility associated with the flow of loans tends to zero.

2.2 Topics in environmental economics

2.2.1 Exploitation of renewable resources: the case of forests

Forests represent one of the first and most important examples of renewable resources that have attracted the attention of the economic literature. One of

⁶To be precise, for technical reasons, the utility function adopted in Fabbri (2017) is different. In particular, it has constant absolute risk aversion and not constant relative risk aversion.

the special characteristics of forests is the long interval between the time when trees are planted and the time when they are cut down, which can also take several decades. This fact makes the age of the trees present in the forest at a certain moment very important.

One of the seminal papers in forestry economic literature is Faustmann (1849). In this work, the author determines the optimal cutting age for a certain population of homogeneous trees: this optimal cutting age is obtained as the one that maximizes the present value of net cash receipts calculated over the infinite chain of planting cycles, from the present to infinity. This idea still showed its power more than one hundred years later when Mitra and Wan (1985, 1986) reformulated the problem in a more modern set-up and in the case of forests with heterogeneous ages. Several extensions and applications of the model were subsequently proposed and the Mitra and Wan model became the main reference for the theoretical literature on forest economics.

In their discrete-time model Mitra and Wan observed how the behaviour of the optimal solution depends on the characteristics of the utility function and the discount rate. In the case of concave utility and zero discount rate, the optimal configuration of the forest converges towards the *sustainable state*⁷ in which all the different generations of trees are uniformly represented, up to the generation corresponding to the optimal age determined by Faustmann. Conversely, in the case of linear utility, Mitra and Wan showed that optimal trajectories are cyclical and that, if the discount rate is positive and the utility is concave, they do not generally converge to a stationary state.

A long series of subsequent contributions generalized Mitra and Wan's results in different directions. We can mention a few of them: the conditions on the function that expresses tree productivity as a function of age have been weakened (see, for example, Khan and Piazza, 2012); the possible costs associated with planting have been added (see Tahvonen, 2004 and the literature cited therein); the possibility of considering different soil types (Salo et al. and Tahvonen, 2002) and tree species (Piazza, 2009, 2010) has been considered; the effects of different property rights on a forest have been studied (Salo and Tahvonen, 1999).

In the article Fabbri, Faggian and Freni (2015), a continuous time version of Mitra and Wan's model is presented. Surprisingly enough, even if in the theoretical literature on forest management of the 1970s and of the early 1980s there were several continuous-time models (see, for example, Kemp and Moore, 1979, Heaps and Neher, 1979, Heaps 1984), our model is the first continuous-time

⁷See the book edited by Kant and Berry, 2005 for a discussion of the ethical aspects of forest management, also in relation to the utility function used.

analogue of Mitra and Wan's (1985, 1986) basic model.

The study undertaken in Fabbri, Faggian and Freni (2015) first shows that some properties found by Mitra and Wan do not depend on the chosen temporal structure (discrete or continuous) : (i) the sustainable state is an optimal (or maximal) steady state for any possible choice of the discount rate and for each utility function (concave and positive) adopted; (ii) when the utility is linear (or, equivalently, when the model is considered as a partial equilibrium problem) the optimal (or maximal) policy is cutting all (and only the) trees that reach the Faustmann optimal age, producing cycles; (iii) if the discount rate is zero and the utility is strictly concave, the system converges, in the long run, to the sustainable state.

Conversely, the study also shows that a series of characteristics of Mitra and Wan's model were due to the choice of the discrete time model. In particular, even if their existence was conjectured by Salo and Tahvonen (2003)⁸ who studied the problem for small (discrete) time, in the continuous time model in the case of positive discount rate and strictly concave utility, one does not have the presence of Faustmann-style cycles.

The paper Fabbri, Faggian and Freni (2015) also contains a methodological contribution: as Wan (1978) had already partially guessed, writing a continuous time model of the type of Mitra and Wan's requires the introduction of more general optimal control problems compared to those usually used in dynamic models with ageing. Indeed, it is necessary to consider controls having values in a space of measures containing Dirac deltas.

Some additional methodological observations inspired by the work Fabbri Faggian and Freni (2015) are contained in Fabbri Faggian and Freni (2017).

2.2.2 Environmental brokers and agri-environment measure

While traditionally environmental economic theory has mainly concentrated on how sustainable development should be promoted/organised by governmental institutions (regulation, taxation, quotas, property rights, permits, label, etc...), less attention has focused on the role that environmental stakeholders, such as individual agents contributing to communities or non-profit environmental organizations, may have in the process of sustainable development in European countries. Indeed, in the most recent political debate, much interest has been given to the formation of groups and organization of citizens dealing with natural resources and their use in the society. The reason is that the emergence of non-government structures to envision a situation that promotes

⁸See also Wan (1994), Tahvonen (2004) and Dasgupta and Mitra, (2011).

green environmental actions into practice, has proven to provide major socio-economic benefits (Dedeurwardere et al 2016). A relevant question is : should policy makers encourage the emergence of such environmental organizations to promote sustainable development into a society?

In Melind-Ghidi, Dedeurwardere and Fabbri (2020) we concentrate on the relation between communities and, in particular, environmental (no-profit) organizations providing goods and services, governmental institutions and economic actors. Scholars in public good economics had already elaborated a set of basic models to explain the existence and the efficiency benefits of cooperation between government and non-profit organizations in complex market economies (see e.g. Weisbrod, 1988, Rose-Ackerman, 1996, Glaeser and Shleifer, 2001). However, less attention has been given to explain the dynamic relationship between the emergence of no-profit environmental organizations, the evolution of producers' willingness to change their management practices and the of consumers' preferences and behaviors.

We theoretically compare an incentive mechanism using intermediaries, such as environmental knowledge brokers and information providers, with a standard central governance mechanism, in terms of environmental impact. We show that the emergence of knowledge intermediaries is particularly effective where farmers initially have low environmental awareness, or when the public institution organising the scheme is insufficiently aware of individuals' characteristics. Our findings provide theoretical support for previous empirical results on payment schemes for agri-environment measures.

The methodological approach links the no-profit organisations' formation theory developed in the literature on environmental science with the process of individual preference formation developed in the economics literature. The former (see for instance Shapin, 1998 and Sverrisson, 2001) has mainly concentrated on the rise of no-profit organisations as a means to connect researchers and their audiences, such as policy makers. The latter is based on adapting models of evolutionary biology to the transmission of cultural traits as initiated by Cavalli-Sforza and Feldman (1981) and introduced into the economics literature, also in a dynamic context, by Bisin and Verdier (1998, 2001).

2.2.3 The insurance value of biodiversity in a dynamic context

According to FAO projections (2018), agricultural production should increase by 70% between 2005 and 2050 to feed a population of 9.1 billion people by 2050. Although this increase in agricultural production must be accompanied by an increase in agricultural yields and an increase in food quality, it is also accompanied by an increase in agricultural land (by 5% per year), to the

detriment of biodiversity. Assessing the phenomenon requires evaluating the trade-off between the short-term increase in agricultural production and the long-term damage of the loss of diversity. This kind of question is part of a broader reflection on the development of a theoretical approach to tools for identifying the economic value of biodiversity. Traditional approaches assess direct and indirect use values (see for example Simpson et al., 1996, in the case of the pharmaceutical industry or Maille and Mendelsohn, 1993) or, in a context of uncertainty, option and quasi-option values (see for example Arrow and Fisher, 1974 or Henry, 1974). In revisiting the issue, more recent studies have introduced and exploited the notion of the *insurance value* of biodiversity. The idea comes from the recognition that biodiversity provides a range of services that have an impact on the variability of ecological (and therefore economic) conditions. This is the case, for example, of regulatory services (control of the activity of local climate, flood control, soil fertility regulation, pollination...) or biocontrol services (pest control, resistance to plant invasion, disease control...). In a series of contributions Baumgärtner (2007), Quaas et al (2007), Quaas and Baumgärtner (2008), Baumgärtner and Quaas (2010) and Baumgärtner and Strunz (2014) proposed how to measure this value and how the reduction in risk premium that can be achieved by conserving biodiversity can be measured.

In the article Augeraud-Véron, Fabbri and Schubert (2019) we formalized this approach in a dynamic context (by being all the previous contributions of static models) by evaluating on the one hand the gain in well-being due to the preservation of biodiversity and on the other hand its insurance value, by generalizing the approach of Baumgärtner and Quaas. In order to better study the impact of risk on optimal decisions in a dynamic context, we follow the approach of Epstein and Zin (1989, 1991, see also Duffie and Epstein, 1992) using recursive preferences. In this way, we are able to distinguish two logically distinct concepts: attitude to time, represented by aversion to intertemporal fluctuations, and attitude to risk, represented by risk aversion. The two have, in terms of their effects on agent behaviour and on the impact on the value of biodiversity, very different effects in the context of the model.

In Augeraud-Véron, Fabbri and Schubert (2020a) we develop a decentralized version of the study presented in Augeraud-Véron, Fabbri and Schubert (2019). In the model 2 farmers (the argument can be extended for an arbitrary number of players) have free access to land, that is a common-property resource. Each farmer chooses the share of land she converts to agriculture, then produces and consumes the harvest from her plot. The evolution of agricultural productivity over time is influenced by the endogenous choices about the size of the plots. More precisely we suppose that the part of land which is not used for farming

is devoted to biodiversity conservation and, in the spirit of the biodiversity insurance value approach, that services from the biodiversity attenuate future uncertainty on agricultural productivity. The two farmers/players coordinate on a Nash equilibrium of the economy.

To understand the impact of decentralization we compare the equilibrium in the strategic competition set-up and the social optimal choice. As expected, since the agents only partly internalize the negative effects of their actions, an over-exploitation of land systematically arises, so that the land available for biodiversity conservation is always lower in the decentralized case than at the social optimum. To investigate the policy implications of the model we show how to decompose the per-capita welfare gain from biodiversity conservation in two parts: the welfare gain of moving from the open access equilibrium to the Nash equilibrium, and the welfare gain of moving from the Nash equilibrium to the optimum. Depending on which of the two is prevalent we can identify in which cases the allocation of property rights is preferable to the introduction of a land conversion tax. In particular we show that enforcing property rights is more relevant in case of stagnant technological progress in agricultural activities (especially for low levels of aversion to fluctuations) while policies consisting in pricing the volatility externality (for instance through a tax on land conversion) are more suited for rapidly developing economics.

2.3 Other works

2.3.1 Optimal control and Hamilton-Jacobi-Bellman equation

A part of my PhD thesis and a series of subsequent works were devoted to methodological issues. More precisely I studied problems concerning the Hamilton-Jacobi equations in Hilbert spaces and problems of optimal control (deterministic and stochastic) in infinite dimensions.

The *dynamic programming* approach connects the study of optimal control problems and the analysis of the related Hamilton-Jacobi-Bellman (HJB) equation. When the optimal control problem is deterministic one has to deal with a first order HJB equation while second order HJB equations are associated to the study of stochastic dynamic optimization problems (see for instance Fleming and Rishel, 1975).

If the state equation (the equation that describes the evolution of the system) is in infinite dimension as it is the case for problems governed by partial differential equations or delay differential equations then the HJB equation is a partial differential equation in infinite dimension (of the first order if the problem is deterministic, see e.g. Li and Yong, 1995 or of the second order if it

is stochastic, see e.g. Fabbri, Gozzi and Swiech, 2017)

Since in general HJB equations (in finite dimension and *a fortiori* in infinite dimension) do not admit regular solutions several approaches arise in the literature to define weaker solutions and they can be classified as it follows:

Strong solutions. This approach was first introduced in Barbu and Da Prato (1986). The solution is defined as a proper limit of solutions of regularized problems.

Viscosity solutions: the solution is defined using test functions that locally “touch” the candidate solution. The viscosity solution approach, initially introduced by Lions (1983) was adapted to Hamilton Jacobi equation in Hilbert space by Crandall and Lion in a series of seven papers⁹

L^2_μ -approach: it was introduced by Goldys and Gozzi (2006). The value function is characterized here in the space of square integrable functions defined on the Hilbert state space H (denoted by $L^2_\mu(H)$) with respect to an invariant measure μ for an associated uncontrolled process.

Hamilton-Jacobi equations in Hilbert spaces and stochastic or deterministic infinite dimensional optimal control were the object of several work I wrote at the beginning of my researcher activity:

- In Fabbri (2008) I give a result of existence and uniqueness for the solution of the HJB corresponding to an optimal control problem driven by a transport equation with boundary control. The boundary control term is expressed, in the HJB equation, by an unbounded operator, so the equation cannot be studied by using standard techniques. An *ad-hoc* definition of viscosity solution is introduced and the existence and the uniqueness of this solution is proved.
- In Fabbri and Goldys (2009) we study a stochastic optimal control problem with a heat state equation on a half line with Dirichlet boundary control and Dirichlet boundary noise. The problem is reformulated by as an evolution problem in a suitable L^2 weighted space. The solution of the problem and its value function are characterized.
- In Fabbri, Gozzi Swiech (2010) we study in abstract form an optimal control problem in infinite dimension. By using the viscosity solution of the HJB equation, we prove a verification theorem and we develop an explicit method for get an ε -optimal control.

⁹All of them had as a title *Hamilton-Jacobi Equations in Infinite Dimensions*. Part I, II, III, IV, V, VI and VII. Many of them appeared on the *Journal of Functional Analysis*.

- In the papers Fabbri (2007, 2008), Fabbri Faggian and Gozzi (2008) we study problems of optimal control with state equation with delay arising in economic models. The delay in the control of the equation translates into an unbounded operator in the infinite dimensional HJB equation. We study existence problem for the solution of the HJB equation. In Fabbri (2007) an explicit solution is given for a certain subclass of problems, in Fabbri (2008) the existence of a viscosity solution for a more general class of problem is provide and finally, in Fabbri Faggian and Gozzi (2008), we give an existence result via strong solution approach.
- In the papers De Girolami, Fabbri and Russo (2014), Fabbri and Russo (2017a, 2017b) we introduce the notion of ν -weak Dirichlet process, we study its property and we use it to develop a new technique to get verification results for stochastic optimal controls problems in Hilbert spaces. Indeed, thanks to the identification of the mild solution of the state equation as ν -weak Dirichlet process, the value processes is proved to be a real weak Dirichlet process. The uniqueness of the corresponding decomposition is used to prove a verification theorem. Through that technique some of the required assumptions are milder than those employed in previous contributions about non-regular solutions of HJB equations and so the theory applies to classes of problems which were not covered from the previous literature.
- Finally in 2017, together with Andrzej Swiech and Fausto Gozzi we completed and published (after a long gestation) the book *Stochastic Optimal Control in Infinite Dimensions: Dynamic Programming and HJB Equations*. In its more than 900 pages it review and systematize all the literature on dynamic programming for stochastic optimal control in infinite dimensional spaces and second order HJB equations in Hilbert spaces. The book also contains several improvements of previous results in the three approaches mentioned above: strong solutions, viscosity solutions and L^2_μ -approach. It also contains an “invited chapter” by Fuhman and Tessitore on the forward-backward approach.

2.3.2 Development Economics

I worked a couple of times on more traditional themes related to the economies of developing countries.

I worked with Michele Di Maio on a model for boycotting goods produced using child labor. In Di Maio and Fabbri (2013) we prove that, in our formalism, considering an heterogeneous agents set-up, the possible perverse effect of

boycott (which, following Basu and Zarghamee, 2009, could also increase rather than decrease child labor), are small and typically overtaken by the positive effect on labor market (general increase of wages and reduction of child labor).

I am also completing a paper with Michele Di Maio and Vincenzo Lombardo on industrial policy in the developing countries. We model a simple economy, populated by heterogeneous entrepreneurs, in which the government uses an Industrial Policy (IP) to influence investment decisions. It is shown how the characteristics of the distribution of skills and the capacity level of entrepreneurs change the characteristics of optimal IP.

Ongoing research and future perspectives

Contents

3.1 Strategic exploitation of resources with spatial dynamics	39
3.2 Strategic interaction and transboundary pollution . . .	44
3.3 Climate Change and Economic Decision Making	49
3.4 Covid-19	50

3.1 Strategic exploitation of resources with spatial dynamics

Despite the recent explosion of aquaculture, overfishing of deep-sea fish stocks has not decreased (FAO, 2016, Cullis-Suzuki and Pauly, 2010) and contributes to the degradation of marine ecosystems, whose criticality is universally recognised and reaffirmed for example in the Paris COP21 agreement (FCCC, 2015).

The mechanism underlying the dynamics of overexploitation mentioned is a classic example (McWhinnie, 2009) of the *tragedy of the commons* in which the strategic competition of different agents (states, fishing companies...) for the use of a common resource leads to an incentive structure in which no one is encouraged (or is encouraged in a very limited way) to take an interest in the global effects of the destruction of the resource. In these circumstances, the role of regulation is essential to restore efficient and sustainable use of the resource.

One of the traditional mechanisms for trying to get agents to *internalize* the aggregate effects of exploitation is to assign property rights on the resource. In the specific case of fisheries resources (Hannesson, 2004), this type of policy often takes the form of TURFS (Territorial Use Right for Fisheries), which consists of giving each agent exclusive authorization to fish in a certain area. The establishment in 1994 of Exclusive Economic Zones (EEZs) adjacent to

all coastal countries by the United Nations Convention on the Law of the Sea (UNCLOS) is a particularly significant example of this policy.

However, the mobility of fish fauna and the presence of migratory species make this type of intervention less effective compared to what happens with the allocation of property rights in other contexts (Munro, 2007, Clarke et al., 2013, see also Janmaat, 2005; White and Costello, 2011; Kaffine and Costello, 2011; Costello et al., 2015; Quérou et al., 2018). The movement of fish through different EEZs diminishes the effect of granting exclusive fishing rights in a given area and the public policy profile needs to take this into account. To formalize this type of mechanism in a model, it is necessary to integrate spatial dynamics in the strategic (fishing) choices of agents.

The situation of fishery resources mentioned so far is an example (particularly emblematic for the truth) of the type of phenomena encountered in the case of natural resources with spatial dynamics. Indeed, a series of similar considerations may apply to other natural resources (renewable or non-renewable) of the same type. Air (or water) pollutants, for example, are rarely stationary at the point of emission, but are spatially diffused; similarly, water reservoirs and some reservoirs of exhaustible resources such as oil deposits have spatial dynamics that may be important for their exploitation.

Despite the importance of the subject and despite the vast literature on the strategic behaviour of agents in models of exploitation of common natural resources (Van Long, 2018), the economic literature shows few attempts to analyse the problem described above by introducing *dynamic spatial games*.

For resources without spatial dynamics, since the seminal article of Levhari and Mirman (1980), stationary Nash Markovian equilibria in models with a common property resource stock have been studied under different hypotheses in the literature (see e. g. Levhari and Mirman, 1980; Clemhout and Wan, 1985; Negri, 1989; Tornell and Velasco, 1992; Dockner and Sorger, 1996; Tornell and Lane, 1999; Rowat and Dutta, 2007; Strulik, 2012a,b; Mitra and Sorger, 2014, 2015a; Dasgupta et al., 2019, and, for literature reviews, Van Long, 2010, 2018). The typical framework is one in which a homogeneous stock, with a known growth function, is harvested by a finite number or mass of identical agents that consume the resource and get un a utility from the consumption. Since Nash Markovian equilibrium analysis is proved to be difficult, explicit results were only obtained for special growth and utility functions (see for example Dockner et al., 2000, Section 12.1 for the case of an exhaustible resource with an iso-elastic instantaneous utility function).

On the other hand, in both growth theory and environmental and natural

resource economics, there is growing interest in the economic effects that occur specifically when resource stocks are subject to spatial diffusion or dispersion processes (see literature reviews of Smith et al., 2009; Xepapadeas, 2010a; Brock et al., 2014a). However, dynamic strategic interaction is largely absent from studies that have introduced spatially dynamic processes into growth or resource models. In these works, the analysis proceeds either on the assumption that rent dissipates instantaneously (see, e.g., Sanchirico and Wilen, 1999), or on the assumption that the planner controls the entire environment (see, e.g., Boucekine et al., 2013b and Fabbri, 2016), or that she takes the spatial distribution of the stock as exogenous (see, e.g., Santambrogio et al., 2019). Clearly, these assumptions are not well suited to the analysis of the spatial externality that occurs when the resource is a distributed mobile spatial stock, but access is limited to a small number of extractors, as in the case of fish. Consequently, very few studies contain analytically or numerically tractable dynamic sets (Bhat and Huffaker, 2007; Kaffine and Costello, 2011; Herrera et al., 2016; Costello et al., 2019; Qu erou et al., 2018; de Frutos and Martin-Herran, 2019).

Perspectives

The purpose for the future is to develop a theoretical framework for the study of strategic space interactions (*war* in the language of Levhari and Mirman) for natural resources on a continuous time basis and to provide an analytically tractable model where the impact of resource movements on the efficiency (in terms of preservation) of space property rights can be reproduced.

This type of approach and the type of results expected remain very different from the contributions found in the literature. Indeed, the two models which, to my knowledge, are closest to this approach are those of Herrera et al. (2016) and Kaffine and Costello (2011) (also used by Costello et al., 2015; Qu erou et al., 2018; Costello et al., 2019). The approach of Herrera et al. (2016) is essentially numerical and focuses only on steady states and, on the other hand, the dynamics in the discrete-time model *N-patch* of Kaffine and Costello (2011) collapses immediately to the steady state and the behavior of the agents does not depend on the distribution of the stock of resources. In both cases, the models do not account for transitions and are not suitable for assessing the welfare of agents by varying policies. In particular, the approach proposed here aims to provide a simple structure where policies such as TURFs or reserve creation can be directly compared to the pure common case (i.e. the absence of any regulation) so that their impact can be assessed.

A very first step in this process was made in the article Fabbri et al. (2020b) where the simplest possible case, that of two countries, is studied. In the model proposed in this paper, to counter the overexploitation of the resource that occurs when players are free to choose where they want to fish, the regulator can establish two spatially structured policies: (i) the creation of a nature reserve (ii) the establishment of TURFs. We show that when technological and preference parameters dictate low fishing effort, the policies described are ineffective in promoting conservation of the resource and, furthermore, lead to a reduction in welfare. Conversely, in a context of increased fishing effort, the intervention can contribute to the conservation of the resource, preventing its extinction while improving the well-being of both players. It is, as far as I know, the first contribution where an explicit Nash equilibrium for the dynamic spatial game of extraction is found and discussed.

One important (and probably the most interesting) element is entirely absent from this first contribution: the role of spatial distribution and dynamics between different locations, which remains, in a two-country model, completely anecdotal.

Already, if we limit ourselves to the policies mentioned, some natural questions arise. For example:

- (i) Where is it more effective to institute a reserve? What should its structure be?
- (ii) Under the TURF, what is the most effective way to partition the territory?
- (iii) How can the institution of reserves be combined with the assignment of exclusive fishing rights? When is one more useful/relevant than the other?

Some of these questions might seem to be more for a natural science researcher than for someone studying economics. In fact, there are some aspects of the problem that undoubtedly need complementary skills, but one of the reasons why biodiversity is in danger in various regions of the world is not linked to natural dynamics but to human behaviour: it is to protect flora and fauna from humans that we create reserves. Human behaviour depends (also) on the incentives that derive from public policies, the study of these incentives is a subject of study for the social scientists and also for those who study economics.

Another relevant question concerns the context of applicability of the policies. A first way of thinking about the problem can be to imagine a situation in which a regulator can impose policies on the whole territory. The optimal policy achieved in this way is certainly a valuable benchmark, but we can imagine

that, especially at international level, a number of conflicting interests make it difficult to apply this benchmark. One question that follows is therefore:

- (iv) what is the second best that each country can implement in case the first best cannot be applied?

Last, we can easily imagine that the policies mentioned are not the only ones that can be tested in the context of the model. Indeed, of course, once a relevant model structure is put in place, it can be used to understand and test whether, depending on the geographical and ecological properties of the system, other types of spatially based policies could be more effective than those currently in use. Trying to understand their structure and their characteristics could be a broad issue that could well be modulated and developed in a PhD thesis.

Approach and Methodology

In order to be able to describe relevant ecological dynamics, to understand how the geographical structure influences strategic behaviour and also to be able to calibrate the model with real data, the spatial structure must be sufficiently general. To this end, it is necessary to be able to describe different geographical conformations, to specify the trajectories of fish fauna and to detail the productivity of their reproduction in the different sub-regions.

To take account of this complexity, the objective is to succeed in working on a generic network structure, with the possibility of specifying the productivity in each node and the potential wildlife flows in each link. The spatial structure thus obtained will support the different fisheries (or, more generally, extraction) policies with a spatial structure such as the creation of fisheries reserves (which, in the model, will have the form of nodes in which no player can fish/extract), open access areas and property rights (nodes in which only one or a certain number of agents can fish).

The spatio-temporal dynamics of the distribution of the resource will therefore depend on its natural conditions of reproduction, its mobility, the conservation policies imposed by the decision-maker and the fishing decisions of the agents (in the different places) that result from them.

This type of framework¹ will be useful for understanding the economic dynamics (in terms of price, for example) that support the behaviour of agents

¹We started looking at it in the preprint Fabbri Faggian and Freni (2020) but an essential part of the work is still there.

in different contexts and, above all, the determinants of the effectiveness of different policies. It will be possible to evaluate the effectiveness of policies in terms of their capacity to preserve and not allow the resource to be depleted; it will be also possible to evaluate the impact, in the context of the model, of regulation on the well-being of agents.

In order to obtain explicit solutions, i.e. to characterize the Nash Markovian equilibrium of the dynamic game with a spatial dimension, a number of simplifying hypotheses will be necessary. In a first step, we will probably work with iso-elastic type agent utilities and linear type production functions. These choices are partly limiting. In fact having iso-elastic utility functions only in terms of consumption does not make it possible to take into account the direct utility that the agents could derive from the protection of the resource. In fact, the possibility of including the resource (or its services) directly in the utility function may be particularly interesting if the agents represented in the model are states. On the other hand, taking into account linear reproduction functions does not allow the phenomena of ecosystem saturation to be considered. Breaking free from these two restrictions in subsequent developments of the model does not seem impossible, especially in the case of a separable utility or for certain families of concave *ad-hoc* production functions.

3.2 Strategic interaction and transboundary pollution

Transboundary pollution is readily recognized as a major topic in the economic literature, notably in the economic geography and environmental economics areas. A key issue posed by transboundary pollution is the treatment of the related externality problem: pollution generated in a certain place may flow integrally or partially to another distant place. Such a problem has been addressed by Candel-Sanchez (2006) in a quite simple theoretical framework, the main objective being the identification of compensation mechanisms to the externality problem posed. Yet, just like in the latter paper, the spatial dimension has not been often accounted for in the related theories developed, and has mostly remained metaphorical, most of the time using the two-country model narrative (see Unteroberdoerster, 2001). Indeed, a large majority of papers in this topic is empirical (see for example, Gibson and Carnovale, 2015, or Henderson, 1996).

This said, an increasing number of theoretical works in the topic of transboundary pollution are introducing an explicit spatial dimension, that's they

are based on a well defined spatial setting. Most of them are static and usually entail an *ad hoc* assumption on the level of pollution at given location. This is clear for example in Hutchinson and Kennedy (2008) and in Arnott et al. (2008).

It is only very recently that there have been some attempts to model the transboundary dynamics as in the contributions of Camacho and Perez-Barahona (2015), de Frutos and Martin-Herran (2019); De Frutos et al. (2019), La Torre et al. (2015, 2018).

In two recent preprints we have begun to work on this subject starting with the analysis of the social optimum. In particular in the preprint Boucekkine et al. (2019a) we construct a spatiotemporal frame for the study of optimal growth under transboundary pollution. Space is continuous and polluting emissions originate in the intensity of use of the production input. Pollution flows across locations following a diffusion process. The objective functional of the economy is to set the optimal production policy over time and space to maximize welfare from consumption, taking into account a negative local pollution externality and the diffusive nature of pollution. The formulation of the model allows to take into account a wide range of heterogeneities between sites that were not present in previous models : (i) differences in natural characteristics (ii) differences in productivity and environmental efficiency of the technologies used (iii) differences in preferences. The model makes it possible to include exogenous growth in factor productivity and technical progress in terms of environmental efficiency. Despite this generality, an explicit solution to the model is found and can be applied to study a first set of questions based on *core-periphery* dynamics in terms of emissions and the effects of preference heterogeneities on investment choices and pollutant accumulation.

Perspectives

One of the limitations of the model presented in Boucekkine et al. (2019a) is the absence of a capital accumulation dynamic. In this context is possible to include some exogenous technological progress but not to produce endogenous growth. A better formulation would include, at the same time, endogenous dynamics of capital accumulation and the spatial diffusion of pollutants. This type of formulation would be much more in line with standard growth models and would produce a strict spatial generalization with pollution of a *textbook* endogenous growth model. Above all, it would make it possible to address, for instance, the following question

- (i) How are growth dynamics (and in particular the growth rate) influenced

by the dynamics of pollution accumulation and vice-versa?

One of the advantages of a model as the one proposed by Boucekkine et al. (2019a) with respect a single-country non-spatial growth model with pollution is that the former makes it possible to study, in a contextual way, the growth process and the evolution of emissions of several countries/regions (with, in principle, different levels of development) and their interactions *via* the dynamics of pollutant accumulation.

A later step is to consider strategic interaction. Indeed, talking about the spatial mobility of pollution obviously amounts to talking about externalities and, in a context where different actors find themselves taking decisions with different objectives, it is also talking about games. Yet, until now, the literature on strategic interaction in spatial environmental models is very thin and, in the case of pollution, there are (to my knowledge) only the recent contributions of de Frutos and Martin-Herran (2019), De Frutos et al. (2019) and Boucekkine et al. (2020).

In these works, partly numerical, the authors show how, due to externalities, countries/players choose excessively polluting strategies (from the point of view of the global optimum) and, more interestingly, that, in a spatial context (when space is homogeneous in terms of economic opportunities and environmental characteristics), countries tend to accumulate their most polluting activities close to borders so that the pollution produced falls as little as possible on their territory. Indeed, even if pollution has a global impact, its negative effects are stronger (at least in the short term) near the place of emission.

It is clear that the inclusion of the spatial dimension in strategic interaction models of pollution opens the way to a series of questions. For example:

- (ii) How are development dynamics affected by externalities and countries' strategic choices?
- (iii) Could we observe the presence of low-growth dynamics due to technology choices (in particular to favouring technologies that pollute more than those that are optimal from the point of view of overall well-being)?
- (iv) How does the equilibria change in different contexts and with different political/geographic characteristics? For example, how does the situation change if a series of countries (e.g. the EU) decides to bargain collectively rather than separately?

The contributions of de Frutos and Martin-Herran (2019) and De Frutos et al. (2019) are very stimulating, but they do not allow for the study of these issues, as they do not take into account the productivity differences between countries and do not include a source of growth (neither exogenous nor endogenous) of the economies. Nor can these issues be analyzed within the framework of the models *à la* Stokey (1998) because of a lack of contextual analysis of the different economies.

A last point that one could study is about regulation.

When we think of international negotiations for the reduction of pollutants, we often think about meetings where different countries converge to negotiate but in terms of their interests vis-à-vis pollutants, countries are much less monolithic than this representation might suggest. For example, different regions of a same country do not benefit from the decisions of the national government in the same way: those chosen for the most polluting productions will suffer more than others from the negative effects of pollution. In fact, anecdotal evidence is rich in examples of movements (and also local institutions) that oppose major development projects decided by national authorities in order to preserve the integrity of the ecosystems present on the territory². A possible working hypothesis is therefore that some decisions taken at the national level tend, on the one hand, not to take sufficient account of global problems of environmental sustainability (because of externalities) and, on the other hand, may conflict with local welfare interests. One could therefore finally think that three different equilibrium dynamics for spatial pollution exist:

- (1) the “global dynamics” of the optimal spatial distribution (in the sense of the social optimum) of the pollution
- (2) the dynamics of spatial distribution that can be implemented in the context of strategic interaction between states
- (3) the dynamics of the spatial distribution of pollution that would be chosen by (small) regions.

The solution in cases (2) would be interesting in itself because it is a situation that is very rarely dealt with. Similarly, situation (3) provides an opportunity to consider what happens when the central government authority is weak or

²Moreover, regional preferences may differ from national preferences for heterogeneities in the natural context and for the behaviour of neighbouring countries.

when the approval of local communities is required (and necessary) before an investment project is carried out. However, the most interesting thing will be to have all three in the same framework to allow us to compare different equilibria and their effectiveness.

Indeed the arguments we have developed above suggest that (2) could be more polluting than (1) and (3) but the geographical differences of the different interactions are complex. One could try to start from the framework proposed above to give the elements to answer the following question: when is the equilibrium (3) closer than (2) to the ideal situation (1)? This question can be reformulated as follows: In an international context where signing a reliable agreement between states is difficult, can “regional” and “local” decisions be more effective in terms of global welfare than national decisions? Is it better (from the point of view of global welfare) to try to increase the bargaining power of local institutions at the expense of national governments in an attempt to move away from (2) and towards (3)? This kind of question are probably large enough also to be a possible initial line for a PhD thesis.

Approach and Methodology

In order to pursue the objectives described, particularly in terms of the relationship between endogenous growth and pollutant accumulation, it will be necessary to have a model with two types of state equations: a diffusion equation (thus a partial differential equation) that describes the evolution of the spatial distribution of pollutants and a (ordinary differential) equation for each site that describes the accumulation of capital. Similarly, to address the second set of issues mentioned it will be necessary to write and solve a multi-player version of the spatial endogenous growth model with pollutant accumulation and diffusion.

The explicit formulation and resolution of such a model seems particularly feasible in the case of separable utility, at least if the disutility of the pollutants is a linear function of the *stock* of the pollutants in the objective functional of the countries and if the utility resulting from consumption is iso-elastic at each site with a location-dependent coefficient.

The last questions require that the behaviour of small regions/communities be microfounded carefully. In fact, if we look only at the externalities linked to the diffusion of pollutants, the decision taken by a government of a small territory should rather be to be free to pollute more, but other more subtle dynamics have to be modelled.

3.3 Climate Change and Economic Decision Making

Context

Of course climate change is one of the big issues facing scientists from different disciplines. One can just have a look to the IPCC reports (see for example the *Fifth Assessment Report*, IPCC, 2014) to understand the magnitude of the phenomenon and its complexity.

With this spirit, I participated to the development of application of the ERC Synergy 2020 project with title *An Interdisciplinary Approach to the Interactions between Biodiversity Loss, Climate Change and Economic Decision Making* (submitted some months ago, it passed the first phase), whose principal investigators are R. Boucekine (Univ. Aix-Marseille), A. Bondeau (CNRS), and A. P. Dobson (Princeton Univ.). It is an interdisciplinary project that brings together dozens of researchers from different fields (economists, natural sciences specialists, agronomists, ecology experts, mathematicians, numerical analysts) working in several countries (France, Brazil, US, UK, Italy). It is a field on which I am taking my first steps but on which I am convinced that it is necessary, given the absolute importance of the issue, to invest time and energy.

The aim of the project is to develop an economic modelling framework that integrates climate change, land use change, the loss of biodiversity, human health and well-being. The basic observation is that damages of climate change affect the well-being in a variety of ways, beyond the direct effects on human productivity that result when temperatures deviates and that scientific and economic pathways to resolve these problems needs to take into account that this crisis is not monothetic, but it is driven at least by three interconnected components, themselves related to other environmental, social and economic dimensions of development: climate, land-use and global economy.

Perspectives

The part of the project on which I will be most active will concern the strategic issues in the fight against global warming. In the benchmark analysis, we will consider, as in the *integrated assessment models* (IAM) type models (see for example Duguy et al. (2013)), a double feedback: on the one hand the sequence economic activity \rightarrow increase in carbon concentration \rightarrow climate change and, on the other hand, the causality climate change \rightarrow damage to economic activity. In the presence of a multi-country/player model, we could study the strategic interactions resulting from the fact that countries only partly internalise the effects of their emissions, leading to overpollution of each country.

To begin, we will consider the case of two countries that maximize (in a standard framework of a growth model) an utility derived from the dynamics of the level of consumption. Each country will have two possible sources of energy: one polluting (and non-renewable) and one renewable and some initial stock of non-renewable resources to use. The evolution of the concentration of CO_2 in the atmosphere will follow, at least in a first formulation, the same approximation (three linear equations) of the carbon cycle introduced by Golosov et al. (2014) and it will be assumed that the real parameters of the total factor productivity (TFP) depend on a damage function of the type introduced by Nordhaus.

Approach and methodology

The elements of the analytical framework described are fairly well established and fairly standard. However, a systematic study of system behaviour in a strategic interaction framework is still missing in the literature.

Our objective is to study the dynamic equilibria of this differential game and to try to characterize the policies and the strategies that would induce global cooperation, particularly in terms of resource transfer among countries.

In a second step, we will use this type of model to study the problems of two countries where climate change has a differential impact on local biodiversity, due, for example, to initially divergent land-use planning policies. This type of framework will allow us to connect the model results to those of other researchers in the project who will be looking at biodiversity dynamics, with the idea that climate change is likely to affect the value humans derive from ecosystem services. To assess this channel we will need to better study the value of services provided by different trophic levels and the sensitivity of different trophic levels to changes in climate variability.

3.4 Covid-19

The outbreak of the COVID-19 pandemic represents, in addition to an epidemiological historical event, an exceptional economic shock. Data from the OECD (2020) suggest that in many countries the loss of GDP due to the presence of the virus and the consequent containment measures will be at least 10%. For this reason, together with the obvious upsurge in medical scientific production on the subject, the phenomenon has had a great echo in economic literature with a strong pressure to merge economic and epidemiological models.

Although I have had contacts with epidemiologists and scholars of population economy for many years, I am not an expert in epidemiology, still I have

participated and continue to participate with some colleagues to produce some contributions on the development of models on economic consequences of the virus diffusion. In this case, as in the case of the models for creating nature reserves mentioned earlier, I believe that people who study economics, even if they are not experts in epidemiology, have specific contributions to make that can finally help us all to look at the situation as a whole.

Two papers have been sent to a journal while some projects remain.

The first is a work written together with Katheline Schubert and Emmanuelle Augeraud-Véron (Augeraud-Véron, Fabbri and Schubert, 2020b) . It is an article that looks at the relationship between the destruction of biodiversity, the emergence of new diseases and epidemics and the effects on economic dynamics. In fact, a rather well established literature (see for instance Halliday et al., and 2020, Morand et al., 2014) shows that there is a relationship between biodiversity loss and the emergence of new zoonoses which have a more or less severe (depending on the situation) impact on the economy. In this work we propose a first stylized model to study the impact of biodiversity conservation on the economic dynamics via the “pandemic frequency” channel. We model the uncertainty of the arrival of a an epidemic outbreak using a Poisson stochastic process (which implies irreversibility due to over-mortality and productivity loss). In addition to preventive intervention determined by the preservation of biodiversity, the planner also has the possibility to decide in the event of a pandemic, a (partial) blockage of economic activity which can be put in place to reduce population mortality, at the cost of a reduction in productive activities.

We characterize the optimal mitigation policy and we show that the optimal biodiversity conservation is greater in more “forward looking” societies (i.e. with a small discount rate) and with a high degree of altruism towards individuals of future generations. As expected we prove that the optimal lock-down is more severe in societies valuing more human life, and that societies accepting a large welfare loss to mitigate the pandemics also do a lot of prevention, not to have to incur the loss too often.

The second is the paper Fabbri, Gozzi and Zanco (2020). To better describe the contribution of the paper we start by remarking that, in the economic literature on COVID-19 a specific effort has been made to integrate epidemiological compartmental models (SIR, SEIR, SEI...) into a macroeconomic dynamic context, see for example the contributions of Alvarez et al., (2020), Eichenbaum et al., (2020), Jones et al., (2020) and Krueger et al.(2020).

These articles look, often numerically, at the trade-off between measures capable of containing contagion and those capable of avoiding economic collapse. However, they model the spread of the epidemic with age homogeneous

epidemiological compartmental models so they cannot take into account one of the characteristic traits of the current epidemic, i.e. the great difference in the effects of the disease among people of different ages.

In order to address this limitation Acemoglu et al. (2020), Gollier (2020) and Favero et al. (2020) (among others) introduce models where the population is divided into a finite number of homogeneous “risk groups” and they study joint economic and epidemiological effects of introducing group-specific policies. Nonetheless in their formulations there is no possibility to move from one group to another and then this kind of approach can take into account the different effects of the disease on different age groups only if it is assumed that the duration of the epidemic is negligible compared to the age range contained in each group. However, this hypothesis is not very likely in the case of an epidemic lasting several years and it is inadequate in the case of diseases that become endemic in the population.

Instead of using age-homogeneous epidemiological compartmental models or epidemiological compartmental models with closed risk groups, it is possible, as we do in Fabbri, Gozzi and Zanco (2020), to describe more accurately the joint dynamics of the epidemic and of the age structure of the population by using explicit age-structured compartmental models, i.e. age-specific epidemiological models with ageing process modeled *à la* Mc Kendrick. This type of models was initially introduced by Anderson and May (1985) and Dietz and Schenzle (1985) and later adapted to numerous contexts and applications, see the books by Iannelli (1995) and Martcheva (2015) for a structured and modern description of the matter.

Our main result is a verification theorem which allows to guess the feedback form of optimal strategies. This will be a departure point to discuss the behavior of the models of the family we introduce and their policy implications.

Perspectives

Two more ideas deserve to be exploited in the next few months.

The first is linked to the work already done with Katheline Schubert and Emmanuelle Augeraud-Véron. Indeed so far we have used the “pandemic reduction” set-up to find qualitative results in terms of how preferences parameters (aversion to fluctuations and risk, discount of future utilities, altruism towards individuals of future generations...) matter, but an extension and a good calibration of the model could try to answer to the question: what is the value of the *pandemic reduction* service of the biodiversity.

In fact, in order to try to give an economic value to biodiversity it is necessary not so much to try to understand what is *the* good way, but to accept that

biodiversity is a multiform concept and that the services it provides are multiple and heterogeneous. Understanding the value of the pandemic reduction service would add a little bit more about our knowledge about the overall value of bio-diversity.

In order to try to progress in this route it is therefore necessary to find in the literature a set of reliable data. A preliminary analysis of the literature suggests that it is not impossible to find some studies that make this exercise doable.

Another project is planned with Davide Fiaschi. The idea is to understand how models of interaction between the epidemiological dynamics and the dynamics of the economy as the ones of Eichenbaum et al., (2020) or Krueger et al.(2020) can be modified and extended to take into account explicitly the mobility of agents. This is, we think, an interesting point, because all the choices about the lock-downs where indeed choices about restrictions of mobility. The problem is not very easy because in a decentralized general equilibrium continuous time model to study the problem two kind of externality are at work: an externality on the productivity of economic activity (if scale returns are not constant) and an externality due to the fact that already infected people do not internalize the total negative effect of their movements for consumption and work behavior. So, economic-augmented SIR model one can look at the dynamic equilibrium behavior of the three groups (Susceptibles, Infected and Recovered) and to optimize on public decisions in terms of sanctions on mobility for producing and consuming.

Approach and Methodology

From a methodological point of view both projects identified are not trivial.

In the first one it is a matter of refining a continuous time stochastic optimization model with non-separable Epstein-Zin preferences and jumps in the form of Poisson processes. As in the recent preprint written with the same coauthors, we will follow the strategy of keeping a problem simple enough to be explicitly solvable in order to obtain transparent and clear results and to be able to calibrate it with the data in a simple way.

In the second case, the continuous time optimization problem for the three classes of agents is likely to result in a forward-backward system of six equations: three forward equations that model the number of people in the three groups (susceptible, infected and recovered) and three backward equations that describe the dynamics of the utilities of the members of the three groups. A priori it is not obvious to show either the existence (which should be easier) or the uniqueness (more difficult) of the system solution.

In this case there will be no hope to find the explicit solution of the model and we will proceed to simulations.

Conclusion

For the past few years, I've been hesitant to apply for the *habilitation à diriger des recherches* being deeply aware that being the thesis supervisor of a doctoral student is not an easy task, that this implies a great deal of responsibility for her/his scientific life and her/his life itself. I didn't go down the road of trying to get HDR carelessly.

Over time I have accumulated a certain number of experiences. As a CR of the CNRS I have been assigned, since September 2017 to the GAEL laboratory in Grenoble where I found a very welcoming and stimulating atmosphere.

In the past, again as a CR, I was assigned to the AMSE laboratory in Marseille. It's been a fantastic period of my scientific life because I was able to take advantage of a privileged working condition in a truly international and rewarding context.

Before that, I spent three years at the University of Evry-Val d'Essonne as a PRAS (PRofesseur ASSocié), Evry was the university that gave me the chance to come in France. It was a role almost assimilated to that of a university professor. My function allowed me to supervise doctoral students but I've always refused knowing that the precariousness of my situation could result in potential difficulties for them.

Previously, I was a researcher at the University of Naples *Parthenope*, it was the university that first gave me the opportunity to have a permanent position. It was also the first university that allowed me to take on responsibilities about PhD students: it has been nine years (since 2011) that I am a member of the doctoral committee of the PhD program in "Economics, Management and Accounting" of the University of Naples *Parthenope*.

I have continued over all these years to research aspects of the theory of the growth and of environmental economics, by developing some "areas", some "zones" of knowledge in which I believe I have the skills to lead young economists on their first steps.

So, the stability of my position, the accumulation of experience, the number of links and perhaps even the advancing age give me more confidence today in advancing the request to be evaluated as a HDR candidate.

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Dynamic modeling in economics: growth and sustainability

Abstract : My current field of research is environmental economics. More specifically, I study dynamic models that seek to understand how agents act and interact in a context of natural resource scarcity and how to articulate public policies to preserve resources and avoid (or at least reduce) overexploitation.

I came to study this type of questions after a scientific itinerary which for several years was centred on the problems of stochastic and deterministic dynamic optimisation in infinite dimensions and, afterwards, on the themes of growth, particularly in the context of vintage capital, spatial growth, optimal population and international finance.

Keywords : Environmental economics, dynamic models, growth theory, optimal control, game theory

Modélisation dynamique en économie : croissance et durabilité

Résumé: Mon domaine de recherche actuel est l'économie de l'environnement. Plus précisément, j'étudie des modèles dynamiques qui cherchent à comprendre comment les agents agissent et interagissent dans un contexte de rareté des ressources naturelles et comment articuler des politiques publiques pour préserver les ressources et éviter (ou du moins réduire) la surexploitation.

Je suis arrivé à l'étude de ce type de questions après un parcours scientifique qui pour plusieurs années a gravité en premier autour des problèmes d'optimisation dynamique stochastique et déterministe en dimension infinie et, après, autour des thèmes de la croissance notamment dans le cadre de modèles de générations de capital, de la croissance spatiale ou encore de la taille optimale de la population et de la finance international.

Mots clés : Économie de l'environnement, modèles dynamiques, théorie de la croissance, commande optimal, théorie des jeux
