Aix-Marseille Université
Faculté d'Économie et Gestion, Aix-Marseille School of Economics
École Doctorale de Sciences Économiques et de Gestion d'Aix-Marseille N° 372

Année 2014-2015

Numéro attribué par la bibliothèque
␣␣␣␣␣␣␣␣␣␣␣␣

Thèse pour obtenir le grade de Docteur ès Sciences Économiques

Environnement et Croissance: Essais sur des Implications des Choix Altruistes des Ménages

présentée par

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soutenue publiquement le 15 juillet 2015

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Avertissement

Mis à part l'introduction et la conclusion de cette thèse, les différents chapitres sont issus d'articles de recherche rédigés en anglais et dont la structure est autonome. Ceci explique la présence des termes *"paper"* ou *"article"* ainsi que l'éventuelle répétition de certaines informations.

Notice

Except the general intorduction and the conclusion, the chapters of this dissertation are self-containing research articles. Consequently, the terms "paper" or "article" are frequently used. This also explains that some informations are given in multiple places of the thesis.

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Remerciements

En préambule de cette thèse, je souhaite adresser mes remerciements les plus sincères aux personnes qui m'ont apporté leur aide et leur soutien pendant ce long chemin qu'est la thèse.

Je tiens tout d'abord à exprimer ma profonde gratitude à mes directeurs de thèses - Carine Nourry et Thomas Seegmuller - qui se sont montrés à l'écoute et très disponibles tout au long de la réalisation de cette thèse. Je les remercie également pour l'aide et les conseils avisés qu'ils m'ont procurés, pour leur sympathie et leur bonne humeur et aussi pour m'avoir permis de travailler sur les thèmes qui me tiennent à coeur. Je leur suis reconnaissante d'avoir guidé mes premiers pas dans le monde de la recherche et des progrès qu'il m'ont permis d'effectuer. J'espère qu'ils sont à présent satisfaits du résultat.

Je veux aussi remercier chaleureusement les membres de mon jury - Alain Ayong Le Kama, Mouez Fodha et Fabien Prieur - de m'avoir fait cet honneur et d'avoir accordé un temps précieux à l'étude de mes travaux. Les remarques et les conseils qu'ils ont pu me donner, notamment lors de la pré-soutenance, ont permis d'améliorer grandement la qualité de cette thèse. En plus de les remercier pour leurs nombreux conseils avisés, je veux également les remercier pour leurs qualités humaines et la sympathie dont ils ont fait preuve à mon égard depuis ma première conférence, où j'ai eu la chance de les rencontrer. Merci également à Mouez pour avoir participé à mon comité de thèse de

deuxième année et pour ses conseils de qualité depuis le début de cette thèse.

Ma gratitude va aussi à l'ensemble des chercheurs du GREQAM et de l'AMSE, grâce à qui j'ai pu profiter d'un cadre dynamique et propice à la recherche tout au long de ma thèse. En particulier, j'adresse mes remerciements à Alain Venditti, pour ses retours et pour sa bienveillance ainsi qu'à Hubert Stahn, pour ses commentaires fort intéressants notamment sur mon deuxième chapitre. Au cours de ma thèse, j'ai également eu l'opportunité de discuter de mes travaux avec de nombreux chercheurs invités que je remercie pour leurs conseils. Je pense notamment à Oded Galor, Omar Licandro, Hélène Ollivier, Katheline Schubert, Dimitrios Varvarigos, Cees Withagen et Anastasios Xepapadeas. Je suis également reconnaissante envers la super équipe administrative de la vieille charité et du château qui nous aide au quotidien. Je pense en particulier à Carole (à qui je souhaite un prompt rétablissement), à Aziza, Bernadette, Elisabeth, Gregory, Isabelle, Mathilde, Yves et Daniel de l'EHESS. J'ai enfin une pensée amicale pour l'ensemble des doctorants anciens et actuels à qui je souhaite une bonne continuation, et notamment à Antoine (Bonleu), Anwar, Bilel, Clémentine, Cyril, Damien, Daniel, Daria, Emma, Eric, Florent, Joao, Justine, Kadija, Lise, Manel, Maty, Nick (merci d'avoir relu mon deuxième chapitre), Nicolas (Abad), Nicolas (Caudal), Paul (Maarek), Pauline, Régis, Thomas, Vincent et Vivien... Je les remercie pour nos échanges et pour nos déjeuners conviviaux au soleil sur les coursives de la vieille charité. Je veux remercier en particulier ceux qui ont partagé avec moi le bureau 203 où l'ambiance était optimale, à la fois très sérieuse et très sympathique, et tous les occupants du château Lafarge (mon deuxième bureau) dont j'abusais de l'hospitalité au moins une à deux fois par semaine, en raison de la très bonne ambiance, un peu familiale, qui y règne. Je tiens aussi à remercier en particulier ceux qui sont également mes co-auteurs Antoine Le Riche et Benjamin Keddad (et sa super moitiée Aude) ainsi que mes formidables ex-voisinnes de bureau Martha, Nastea et Natacha pour leur gentillesse. Je suis ravie d'avoir pu partager cette expérience avec vous.

J'ai eu la chance de passer ma dernière année de thèse à EconomiX (Université Paris Ouest Nanterre la Défense). Cela a été l'occasion de rencontrer beaucoup de gens très sympathiques et de participer à de nombreux séminaires en économie de l'environnement que j'ai grandement apprécié. Un très grand merci à Natacha Raffin pour son accueil, ses nombreux conseils et sa gentillesse. Merci à Luc Désiré Omgba pour m'avoir permis de présenter au séminaire DDEEP (deux fois) et pour ses retours sur mes derniers chapitres. Merci à Johanna Ethner pour sa sympathie et encore un grand merci à Alain Ayong Le Kama pour son accueil très chaleureux à Nanterre. Merci à mes collègues de bureau, Alzbeta, Omar, Sylvia, Zouhair, avec qui il était très agréable de partager cette dernière année de thèse (même si j'étais toujours trop débordée pour vos sorties parisiennes).

J'adresse une pensée particulière à mes amis, notamment à Ade, Chris, Ben, Quentin, Marion, Matthias, Camille et Nico, qui m'ont toujours soutenu et qui m'ont permis de m'évader des petits tracas associés à la thèse. Merci à vous pour votre présence tout simplement. Je voudrais aussi témoigner de ma vive reconnaissance envers Chantal et Hervé pour leur soutien et leur aide pour la relecture de l'introduction.

J'exprime aussi et bien sûr mes sincères et profonds remerciements à Marion Davin et Gilles De Truchis, à qui je dois énormément. Vous êtes présents et vous me soutenez depuis très longtemps! Partager cette expérience avec vous m'a été d'une grande aide. Marion, on s'est rencontrée en première année de fac à Aix et on est très vite devenue amie. C'est une chance incroyable d'avoir pu partager tout cela avec toi. Je tiens à te remercier pour tout, merci de m'avoir acceuillie si souvent chez toi et surtout merci m'avoir épaulé et encouragé! En plus d'une amie extra, tu es aussi devenue une super co-auteure et j'espère que l'on pourra collaborer très longtemps! Gilles, cela fait maintenant douze ans que tu me supportes. Merci pour ta patience, tes conseils et ton soutien sans faille dans mes moments de doutes! Cette expérience n'aurait pas été la même sans toi.

Enfin, je dédie cette thèse à ma famille et en particulier à mes parents, mes frères et mes grand-mères qui m'ont soutenu dans mes très longues études et dans le choix de faire de la recherche. Merci à tous pour votre confiance et votre gentillesse! Vous m'avez toujours sensibilisé à l'importance de l'environnement et de la transmission aux générations futures et vous n'êtes donc pas étrangers aux thèmes dont traite cette thèse.

CHAPTER 0

Introduction générale

0.1 Avant propos

Les dernières décennies ont été marquées par une prise de conscience accrue des problèmes environnementaux, comme en témoigne l'ampleur des débats publics nationaux et internationaux sur ce sujet. Une des questions centrales soulevées par ces débats est celle de la possibilité d'une croissance davantage respectueuse de l'environnement, d'un développement durable qui ne serait pas dommageable aux générations futures. L'accumulation de problèmes environnementaux engendrés directement ou indirectement par l'activité humaine semble être au cœur d'une telle prise de conscience. Parmi les dégradations de l'environnement naturel, on peut citer la pollution de l'air, des sols et de l'eau, la déforestation ou la surexploitation des ressources. Ces dommages étant inter-connectés, ils ont de surcroît tendance à se renforcer mutuellement. Par exemple, la perte de biodiversité végétale (forêts, zones humides, coraux *etc.*) affecte la capacité d'absorption de la pollution et amplifie ainsi les émissions de pollution. Des catastrophes écologiques majeures interviennent également du fait de notre activité. Les accidents nucléaires de Tchernobyl en 1986 ou de Fukushima en 2011, les accidents industriels chimiques de Seveso en 1976 ou de Bhopal en 1984, ou encore les marées noires en sont des exemples marquants. De façon générale, l'ensemble de ces dégradations a ainsi abouti à la raréfaction des ressources naturelles, à l'extinction de nombreuses espèces animales et végétales, à l'acidification des océans, ou encore à un changement climatique planétaire.

Si l'analyse détaillée de ces dommages environnementaux n'est pas l'objet de cette thèse, ils soulèvent de nombreuses questions quant aux interactions entre les sphères économique et environnementale car le développement a des effets négatifs sur l'environnement, mais en retour la pollution nuit également aux Hommes et à l'activité économique, en dégradant les possibilités de production ainsi que le bien-être et la santé des agents. Il est donc indispensable d'identifier la manière dont ces sphères interagissent afin d'évaluer comment pallier aux problèmes soulevés. Ces questions essentielles pour nos sociétés ne cessent de prendre de l'importance dans les débats publics, mais aussi scientifiques. L'économie de l'environnement s'attache justement à intégrer la dimension environnementale dans des modèles économiques afin d'apporter des réponses à ces débats. Comme le soulignent Brock & Taylor (2005), *"la théorie de la croissance nous offre des outils essentiels à l'exploration du lien entre les problèmes environnementaux d'aujourd'hui et la vraisemblance de leur amélioration demain"*, c'est pourquoi nous utiliserons tout au long de cette thèse ce type de structure. De plus, nous voulons porter une attention particulière au rôle central des ménages dans la relation entre croissance et environnement, parce que leurs choix sont déterminants à un niveau agrégé s'agissant des effets de l'économie sur l'environnement (consommation polluante, émission de déchets, taille de la population *etc.*) et parce qu'ils sont également les premiers touchés par les dommages environnementaux, ce qui engendre une modification de leurs comportements. L'objectif de cette thèse est alors de compléter la compréhension théorique des conséquences des choix des ménages sur les interactions entre les sphères économiques et environnementales, mais aussi de proposer des recommandations politiques pour solutionner les problèmes en découlant.

Dans cette introduction, nous nous attacherons à détailler les interactions entre les dimensions économiques et environnementales, en rappelant d'abord les effets de la croissance sur l'environnement puis les effets réciproques de l'environnement sur la croissance. Nous mettrons ensuite en exergue le rôle des ménages dans cette relation ainsi que l'importance de la mise en place de politiques environnementales.

0.2 Lien croissance environnement

0.2.1 Effet de l'activité économique sur l'environnement

Par le biais de la production et de la consommation de biens, l'activité humaine utilise des ressources naturelles et génère des déchets solides, gazeux et liquides. Si individuellement, certains de ces effets peuvent apparaître comme non significatifs, leur cumul exerce une pression importante sur l'environnement, qui a engendré des dégradations majeures au cours de notre Histoire (comme nous avons pu le souligner précédemment).

Le développement économique affecte la qualité environnementale par de multiples canaux. Ehrlich & Ehrlich (1981) résument les déterminants principaux des dommages environnementaux d'origine anthropique grâce à la fameuse équation d'impact $I = PAT$. Ainsi, alors que la taille de la population P et le niveau moyen de consommation par individu A indiquent le volume de l'activité économique, la nature de la technologie T définit le caractère plus ou moins polluant et consommateur en ressources de cette activité. Au delà de cette équation descriptive, une caractéristique importante à ne pas négliger est que chacune de ces composantes est endogène et va interagir avec les autres. La relation entre environnement et croissance est donc appelée à évoluer avec le développement même de l'économie. Dans ces conditions, il semble indispensable de comprendre comment la relation croissance-environnement a évolué au cours du temps. Cette analyse est l'objet de la section suivante.

Évolution de l'impact du développement sur l'environnement au cours du temps

Afin d'évaluer cette relation, il est important de comprendre le processus de développement et ses caractéristiques. La théorie de la croissance unifiée, introduite par Galor & Weil (1999) et résumée par Galor (2005), s'est justement attachée à identifier les différents régimes de développement économique, leurs caractéristiques et les facteurs déterminant les changements de régimes. Si cette littérature ne considère pas les effets du processus de développement sur l'environnement, elle nous permet de remarquer les variations majeures de la relation entre la croissance économique et la croissance de la population au cours du temps, de même que l'évolution de la nature du progrès technologique, deux éléments clefs des conséquences de l'activité économique sur l'environnement. Dans cette section, nous allons donc utiliser cette structure pour détailler les évolutions majeures du développement et les conséquences que cela a pu avoir sur l'environnement.

Tout d'abord, il est à noter que trois phases de développement sont identifiées. La première, correspondant à la majeure partie de l'activité de l'Homme, est appelée *régime Malthusien*, en référence à Malthus (1798) dont la théorie capturait les caractéristiques de l'époque à savoir une stagnation du PIB par tête et un taux de croissance de la population fortement lié à celui de la croissance économique. Le second régime débute avec le processus d'industrialisation. Il est donc marqué par une forte accélération du progrès technique et du PIB par tête. Cette hausse de la richesse par individu est cependant amoindrie par l'augmentation de la taille de la population, qui reste très corrélée aux variations du PIB à ce stade. C'est pourquoi, Galor & Weil (1999) nomment cette seconde étape de développement *régime post-malthusien.* Enfin, le troisième et dernier régime est celui dans lequel les pays développés se trouvent actuellement, d'où son nom de *régime d'économie moderne.* Il est associé à une croissance importante permise par un progrès technologique toujours grandissant mais aussi par une transition démographique, inversant la relation entre croissance économique et croissance démographique. Nous allons d'abord détailler les conséquences environnementales de l'entrée dans le processus d'industrialisation, puis nous analyserons les implications du passage au dernier régime.

Processus d'industrialisation et environnement: l'Anthropocène

Si l'Homme a toujours impacté son environnement, cet effet s'est fortement intensifié avec la révolution industrielle. En effet, l'industrialisation de l'activité économique s'est caractérisée par une augmentation sans précédent de la production, permise par le progrès technique, mais aussi de la taille de la population. De plus, le processus de production s'est développé sur la base de technologies très polluantes, centrées sur l'utilisation de combustibles fossiles (charbon en particulier), et a été associé à une urbanisation importante des territoires. L'ensemble de ces éléments a ainsi conduit à un accroissement majeur des émissions de pollution et de la dégradation des ressources. Depuis, l'impact de l'Homme sur l'environnement et la planète est tel que de nombreux géologues soutiennent que la révolution industrielle marque l'entrée dans une nouvelle ère géologique. A l'origine de ce mouvement, Paul Crutzen, prix Nobel de chimie de 1995 pour ses travaux sur l'atmosphère et la couche d'ozone, et Eugène Stoermer proposent de nommer cette nouvelle ère « Anthropocène » pour illustrer son origine anthropique (Crutzen & Stoermer , 2000). L'humanité est ainsi devenue une force géologique capable de modifier l'ensemble des phénomènes climatiques, géologiques et biologiques de la planète (changement climatique, acidification de l'océan, disparition de nombreuses espèces naturelles. . .). Ce constat est très largement partagé par les scientifiques et ce terme est de plus en plus utilisé (*e.g.* Zalasiewicz *et al.* , 2008 ; Zalasiewicz *et al.* , 2015), bien qu'il soit encore informel.

Depuis ce tournant majeur de la relation environnement-croissance, la dégradation de l'environnement générée par le développement économique a continué à s'aggraver à l'échelle mondiale jusqu'à maintenant. Une illustration de ce phénomène peut être trouvée dans le graphique ci-dessous représentant les concentrations de deux des principaux gaz à effet de serre (dioxyde de carbone et méthane). L'étude de ce tournant semble donc importante, c'est pourquoi nous proposerons dans le premier chapitre de cette thèse un modèle pour expliquer le processus d'industrialisation polluante, en particulier par le biais des choix des ménages.

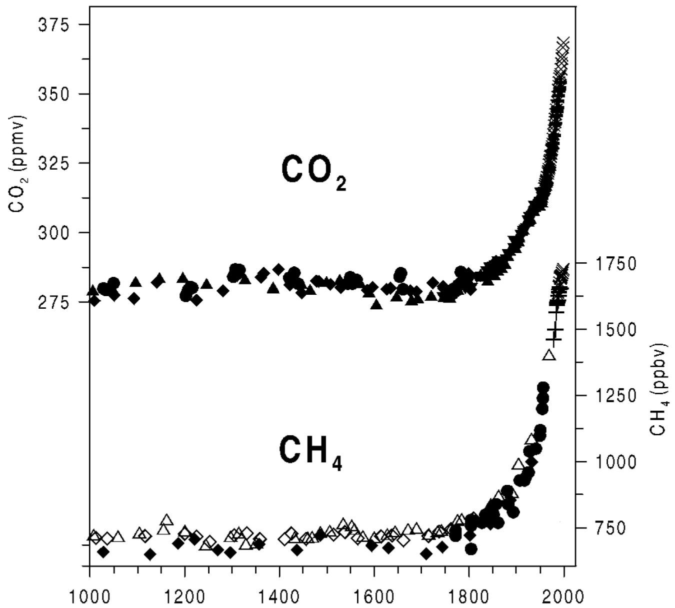


Figure 1: Évolution des concentrations atmosphériques du dioxyde de carbone CO_2 et du méthane CH_4 pendant le dernier millénaire. *Source: Stauffer* et al. *(2002).*

Régime d'économie moderne et environnement: le rôle du capital humain

La relation monotone observée entre le développement économique et l'environnement pourrait cependant être modifiée dans le dernier régime de développement, en raison de la place importante qui y est accordée au capital humain et des conséquences que cela implique en termes de population et de production.

En effet, même si les innovations techniques et technologiques ont toujours eu un rôle prépondérant dans le processus de développement depuis le début de l'industrialisation, les besoins en capital humain associés à ces innovations ont beaucoup évolué (voir Bairoch , 1997 ou Galor , 2005 pour une revue des évidences empiriques). Dans les premières phases de développement, la production nécessitait surtout d'une quantité importante de main d'œuvre non qualifiée et le capital humain n'avait qu'un rôle limité. Puis, au fur et à mesure du progrès technique, la nature des innovations de plus en plus complexe a impliqué des besoins croissants en formation de la force de travail afin qu'elle s'adapte rapidement à ces changements technologiques constants. La demande grandissante des entreprises pour des travailleurs qualifiés dans la deuxième phase de l'industrialisation a ainsi joué un rôle central dans le processus de développement parce qu'elle a permis d'accélérer encore le progrès technologique et parce qu'elle est à l'origine de la transition démographique, correspondant à l'inversion du lien entre développement et croissance de la population.

Le mécanisme à l'origine de la transition démographique, mis en évidence par Galor & Weil (1999, 2000), repose sur l'effet de la hausse de la demande en capital humain sur l'arbitrage des parents, dit "qualité-quantité", entre le nombre d'enfants qu'ils souhaitent avoir et l'éducation qu'ils souhaitent prodiguer à chacun d'entre eux. De façon similaire à la première phase de l'industrialisation, la hausse du progrès technologique implique un effet revenu positif, qui permet aux ménages de dépenser plus pour leurs enfants. Cependant, étant donné que la hausse du progrès correspond maintenant à une augmentation importante du capital humain, deux effets en faveur de la "qualité" des enfants apparaissent. Premièrement, la valorisation grandissante du capital humain rend le rendement de l'investissement en éducation de plus en plus grand. Deuxièmement, la hausse du capital humain des parents augmente le coût d'opportunité associé au temps passé à élever leurs enfants.[1] La deuxième phase de l'industrialisation induit ainsi une substitution de la quantité des enfants par leur qualité et donc une transition

[1] Ces effets sont également renforcés par le fait que le travail des enfants, très utilisés pendant la première phase de l'industrialisation, devient moins attractif et acceptable avec la hausse de la demande et du niveau de capital humain (voir par exemple Hazan & Berdugo , 2002).

démographique, grâce à laquelle la croissance de la population diminue maintenant avec le développement.

L'entrée dans cette nouvelle phase de développement a des effets multiples sur l'environnement, notamment par la modification des comportements démographiques et de celle du processus de production.

Toutes choses égales par ailleurs, la baisse de la croissance de la population bénéficie à l'environnement en soulageant la pression, ou du moins la hausse de la pression, exercée en termes de consommation de ressources et d'émissions de pollution. Pourtant, la pollution globale a continué d'accélérer alors que les pays développés entraient dans le dernier régime de développement au milieu du $XX_{ième}$ siècle. Pour expliquer ce fait, il est important de souligner les fortes disparités internationales en termes de développement. En effet, l'entrée des pays développés dans le régime d'économie moderne au milieu du $XX_{ième}$ siècle, permettant une baisse de la croissance de la population de ces pays, a coincidé avec le début de l'industrialisation de la plupart des pays en développement, correspondant au contraire à une augmentation massive de leur croissance démographique. Au cours du vingtième siècle, la population mondiale a ainsi fortement augmenté, passant de 1.6 à 6.1 milliards d'individus. Désormais, la plupart des pays ont commencé à diminuer leur taux de fécondité (Reher , 2004). Les Nations Unies estiment que la croissance de la population mondiale devrait diminuer pour atteindre une population d'environ 9,6 milliards d'individus en 2050 et se stabiliser à 10,9 milliards à partir de 2100 (United Nations , 2013). Il convient donc de modérer l'aspect positif que représente la baisse de la croissance de la population pour l'environnement, car, malgré cela, l'effectif total de la population restera à des niveaux très importants correspondant à une pression environnementale très élevée.

Pour évaluer le caractère soutenable de la pression environnementale de la consommation mondiale, nous pouvons utiliser l'indice d'empreinte écologique, proposé par Rees & Wackernagel (1994) à cet effet. Cet indicateur physique correspond à la surface nécessaire pour satisfaire la consommation d'une population et assimiler les déchêts associés pour une date donnée.[2] Le rapport Planète Vivante de la WWF (2014) indique ainsi que: *"Depuis plus de quarante ans, la demande de l'humanité excède la biocapacité de la planète - c'est à dire la surface de terres et de mers productives nécessaires pour régénérer ces ressources"*. Ce rapport révèle également qu'en 2010, l'humanité nécessitait l'équivalent d'une planète Terre et demie pour satisfaire ses besoins en ressources et absorber ses déchets, soit le double de l'empreinte de 1961. Toutes choses égales par ailleurs, les prévisions des Nations Unies concernant la taille de la population mondiale ne semblent donc pas soutenables à terme. De plus, l'augmentation constante de l'empreinte écologique ne s'explique pas uniquement par la croissance de la population, étant donné que l'empreinte écologique par tête s'aggrave également. L'empreinte écologique par habitant des pays à haut revenu étant aujourd'hui cinq fois plus élevée que celle des pays à bas revenu (WWF , 2014) du fait de leur consommation bien plus importante, on peut s'attendre à ce que les quantités consommées par les pays en développement s'accentuent et à ce que leur empreinte augmente à l'avenir.[3]

Les éléments que nous avons pris en compte jusqu'à présent correspondent surtout aux volumes de production associés au développement, notamment par le biais de la population. En accord avec l'équation d'impact d' Ehrlich & Ehrlich (1981) énoncée au début, la taille de la population est un élément déterminant de l'effet de l'Homme sur la planète, mais la nature et l'intensité de l'activité économique sont également au coeur de cet effet. Dans un papier fondateur, Grossman & Krueger (1991) identifient trois effets majeurs exercés par le développement de l'activité économique sur l'environnement: un effet d'échelle, un effet de composition et un effet technique.

Au delà de l'aspect démographique énoncé précédemment, le développement économique correspond, par définition, à un accroissement de la consommation et de la pro-

[2] Pour une critique de cet indicateur, voir par exemple Neumayer (2004).

[3] L'empreinte écologique d'un pays prend en compte les ressources et les déchets correspondant à la consommation d'un habitant moyen de ce pays (peu importe où ils ont été produits).

duction. Il occasionne ainsi une augmentation des besoins en facteurs de production et une hausse des émissions de déchets. Si la nature de l'activité reste inchangée, le développement tend donc à accélérer la dégradation de l'environnement par un *effet d'échelle*.

L'*effet de composition* correspond à l'évolution du système productif et peut affecter l'environnement négativement ou positivement. Dans les premiers stades de développement, la production évolue d'une économie agricole et rurale à une économie urbaine et industrielle, ce qui augmente considérablement la dégradation environnementale. Cependant, à des niveaux de développement plus avancés, l'économie s'oriente vers des activités moins polluantes, telles que la production de service ou de biens moins intensifs en facteurs polluants. Cet effet représente l'évolution de la nature de l'activité économique et s'avère donc déterminant lorsqu'il s'agit d'évaluer les conséquences environnementales de la croissance.

Enfin, l'*effet technique* est défini par un changement de techniques de production. Si dans les premières étapes de développement, la technologie peut correspondre à davantage de pollution (e.g. agriculture intensive), le progrès technique permet aussi d'atteindre une meilleure efficacité environnementale de l'appareil productif. En effet, même si le capital humain des travailleurs est axé sur la recherche de substituts et le développement de nouvelles technologies en dehors de considérations environnementales dans un premier temps, l'amélioration de l'efficacité du processus de production peut conduire à une diminution des besoins en ressources par unité produite et à une utilisation moins intensive de facteurs polluants. Toutes choses égales par ailleurs, l'amélioration de la productivité peut ainsi diminuer les émissions de pollution, même si cela n'est pas l'objectif initial. De plus, le progrès technique rend également possible l'existence de technologies spécifiquement créées pour diminuer les émissions de pollution. Cet effet est conduit par des mécanismes complémentaires liés aux préférences, plaidant en faveur d'une prise de conscience des problèmes environnementaux et de leurs enjeux.

En effet, l'accumulation du savoir permet aux agents de prendre conscience du rôle de l'environnement sur l'activité économique (sur la santé, sur la raréfaction des ressources nécessaires...), tandis que l'augmentation de la richesse leur permet de dépasser un objectif de survie et d'être capable d'agir.[4] L'effet technique indique donc que la croissance économique est également amenée à permettre le développement de technologies vertes, qu'elles correspondent à des technologies moins polluantes ou des technologies de dépollution.

Il apparaît donc clairement que la relation environnement-développement évolue au cours du temps et que sa nature est déterminée par les poids relatifs des différents effets énoncés.

Question de la compatibilité entre développement et environnement

La baisse de la croissance de la population, accompagnée de l'accélération du progrès technique et de l'augmentation de la place accordée au capital humain nous permet donc d'envisager un développement économique davantage compatible avec l'environnement. Mais est-ce vraiment possible? Cette question est centrale en économie de l'environnement et plus globalement pour nos sociétés. Dans cette section, nous présenterons les principaux courants de pensées ainsi que les justifications théoriques et empiriques avancées.

Club de Rome et croissance zéro

Dans les années 1970, les travaux du club de Rome (Meadows *et al.* , 1972) se sont attachés à répondre à cette question et ont ainsi permis d'informer et de sensibiliser l'opinion publique sur les dangers que peut représenter la croissance économique sur l'environnement. Les conclusions de ce rapport sont très pessimistes. Au delà des travaux passés comme ceux de Malthus (1798), Ricardo (1817) ou Jevons (1865)

[4]Une analyse détaillée des canaux par lesquels l'environnement affecte l'économie d'une part, et de l'évolution des comportements, d'autre part, est effectuée respectivement dans les sections 0.2.2 et 0.3.1.

qui concluaient qu'une croissance économique nulle était une fin inévitable en raison du caractère limité des ressources, ce rapport préconise une *croissance zéro* afin d'éviter une catastrophe économique à venir. En se focalisant sur la dimension environnementale, le Club de Rome considère que la dégradation environnementale engendrée par l'activité économique est inéluctable et conclut ainsi que la seule solution pour assurer la subsistance de l'environnement est de stopper la croissance économique. Cependant, cette étude de même que les travaux plus anciens de Malthus (1798), Ricardo (1817) ou Jevons (1865) partent de l'hypothèse que la technologie de production et les comportements, notamment en termes de population et de consommation, n'évoluent pas. Elles ne prennent donc en compte que l'effet d'échelle associé au développement. Or, comme on a pu le voir précédemment, la nature même du développement est appelée à évoluer avec l'amélioration des connaissances et l'accélération du progrès technique qui le définissent. Il est donc très difficile d'anticiper les tendances futures du développement économique (découvertes de substituts, développement de procédés moins polluants, modification des comportements...). Les prévisions pessimistes de Malthus (1798) d'une croissance exponentielle de la population annulant la croissance économique de long terme ont, par exemple, été remises en cause par le processus de transition démographique permis par l'accumulation du capital humain. Les conclusions extrêmes de ce rapport, pré-supposant une incompatibilité totale entre les dimensions économique et environnementale, pourraient donc être remises en question.

Développement durable

Dans les années 1980, une autre vision moins restrictive de la relation environnement-croissance apparaît: le *développement durable*. Il ne s'agit alors plus seulement du niveau de la croissance économique mais surtout de sa nature. Ce concept fut introduit dans le rapport *World Conservation Stategy* (IUCN , 1980), puis popularisé par le rapport *Our Common Future*, plus connu sous le nom de rapport Brundland (WCED

, 1987). La plus célèbre définition du concept de développement durable est issue de ce dernier: *"Le développement durable est celui qui répond aux besoins du présent sans compromettre la capacité des générations futures à répondre à leurs propres besoins"*. Outre l'aspect intergenérationnel de ce concept illustré par cette définition et rappelé au sommet de la Terre de Rio en 1992, un autre élément clef est son caractère multidimensionnel. Le sommet de la Terre de Johannesburg en 2002 précise ainsi dans ses objectifs l'importance de *"l'intégration des trois composantes du développement durable – développement économique, développement social et protection de l'environnement – en tant que piliers interdépendants qui se renforcent mutuellement"* (United Nations , 2002). Le développement ne peut être soutenable que s'il intègre des préoccupations à la fois environnementales, économiques et sociales. Sans une bonne qualité environnementale, le développement ne peut être viable, tandis qu'au sein d'une société en mauvaise santé économique et sociale, la protection de l'environnement ne peut être suffisante et sa qualité ne pourra être maintenue à terme. Pour assurer la pérennité de nos sociétés, le développement économique doit donc répondre à des objectifs de préservation de l'environnement, mais aussi d'équité sociale intra- et inter-générationnelle, c'est à dire limiter les inégalités entre les membres d'une même génération comme entre les différentes générations. Le but d'un décideur public est alors de trouver le juste équilibre entre ces objectifs complexes et possiblement contradictoires, d'où sa difficulté. Dans cette thèse, nous nous intéressons aux trois piliers en étudiant la relation environnement-croissance et les inégalités qui peuvent en découler. En particulier, dans le chapitre 2, nous révèlerons l'existence d'inégalités intergénérationnelles, c'est à dire entre les générations, provenant de variations des comportements verts des agents, tandis que dans le chapitre 3, nous étudierons les inégalités intragénérationnelles, c'est à dire au sein d'une génération, en lien direct avec la répartition inégale des effets de la pollution sur la santé.

La définition du développement durable étant assez générale, elle donne lieu à de nombreuses interprétations, comme le souligne Pezzey (1989). En particulier, deux types de soutenabilité sont souvent retenues. Selon la durabilité dite faible, le caractère soutenable du développement est assuré par la "capacité à produire du bien-être économique" (*cf.* Solow , 1993). Toutes les formes de capital sont fortement substituables (capital physique, capital humain et capital naturel), aussi la soutenabilité correspond à la préservation du stock de capital agrégé de l'économie peu importe sa nature. Au contraire, la soutenabilité forte considère que les différents types de capitaux sont peu (ou pas) substituables (voir Daly , 1974). L'environnement a une valeur intrinsèque et sa qualité doit être préservée afin que le développement soit durable. Par la suite, lorsque nous parlerons de développement durable, nous ferons surtout référence à cette deuxième définition, c'est à dire à un état où la qualité environnementale ne se dégrade pas.

Courbe de Kuznets Environnementale

Dans ce contexte, la littérature empirique a cherché à évaluer l'effet du développement sur l'environnement et à tester si le développement était entré dans une phase durable.[5] Si tout le monde s'accorde sur le caractère polluant de l'activité économique dans les premiers stades de développement, la question est de savoir si cette relation est monotone ou si elle pourrait s'inverser pour des stades de développement plus avancés.

Grossman & Krueger (1991) identifient une relation en U inversé entre le revenu par tête et le niveau de la pollution. Un tel résultat implique que la croissance économique s'accompagne d'une dégradation environnementale dans les premières étapes de développement, tandis qu'elle permet au contraire d'améliorer les conditions environnementales à partir d'un certain seuil de revenu par tête. En référence à l'article de Kuznets (1955) qui identifiait une relation similaire entre les inégalités de revenu et le revenu par tête, Panayotou (1993) nomme cette relation non monotone la Courbe de Kuznets Environ-

[5] Nous retenons dans cette thèse une définition forte de la soutenabilité, dans le sens où elle s'exprime en termes d'environnement et non de stock de capital agrégé.

nementale (CKE). Depuis, de très nombreuses contributions empiriques et théoriques ont cherché respectivement à confirmer ou infirmer cette relation et à expliquer les raisons pour lesquelles elle pourrait exister.

L'intuition sous-jacente à une telle relation est résumée par Dasgupta *et al.* (2002): *"In the first stage of industrialization, pollution in the environmental Kuznets curve world grows rapidly because people are more interested in jobs and income than clean air and water, communities are too poor to pay for abatement, and environmental regulation is correspondingly weak. The balance shifts as income rises. Leading industrial sectors become cleaner, people value the environment more highly and regulatory institutions become more effective."* Cette citation met ainsi en lumière les principales justifications avancées, à savoir une évolution du processus de production, des comportements des ménages et de la régulation, toutes trois interconnectées.[6]

La modification de l'appareil productif tient aux interactions entre les trois effets (d'échelle, de composition et technique) exposés précédemment. Grossman & Krueger (1991) expliquent donc que pour des stades de développement avancés, la production devient moins polluante en s'orientant vers des secteurs moins intenses en pollution par nature (service par exemple) mais aussi en adoptant des technologies moins polluantes. La courbe entre donc dans une phase descendante dès que les effets positifs du développement sur l'environnement, à travers l'effet de composition et l'effet technique, surpassent les effets négatifs liés à l'effet d'échelle. Dans ce sens, Stokey (1998) reproduit la CKE à partir d'un modèle dans lequel la production doit se contenter de technologies très polluantes dans les premiers stades de développement, tandis que des technologies de plus en plus *vertes* peuvent être utilisées au delà d'un certain seuil de capacités productives.

S'agissant des comportements des ménages, le principal argument mis en avant est que pour des niveaux de vie faibles, les agents se concentrent sur leurs besoins de survie,

[6] Voir Dinda (2004) pour une revue de la littérature complète sur la courbe de Kuznets environnementale et ses déterminants.

alors qu'ils peuvent accorder davantage d'importance à l'environnement lorsque leur niveau de vie s'améliore. Grâce à des modèles théoriques, John & Pecchenino (1994) et Selden & Song (1995) reproduisent la courbe de Kuznets environnementale en mettant en avant l'existence d'un seuil de revenu en dessous duquel les agents se focalisent sur leur consommation et au dessus duquel ils investissent en maintenance environnementale, c'est à dire en protection de l'environnement, de sorte que les émissions nettes de pollution diminuent une fois ce seuil franchi.

La régulation environnementale est également identifiée comme un déterminant majeur de l'existence d'une relation positive entre croissance et qualité environnementale. L'efficacité de la régulation est susceptible d'évoluer avec le développement pour deux raisons principales. Le développement permet de renforcer les institutions de sorte qu'elles puissent implémenter une politique efficace (*cf.* Jones & Manuelli , 2001). De plus, la modification des comportements, associée au processus de développement, permet aux ménages d'accepter plus facilement une politique de protection environnementale et même d'en faire davantage la demande (*cf.* Dinda , 2004). Dans ce sens, Arrow *et al.* (1995) rappellent que *"in most cases where emissions have declined with rising income, the reductions have been due to local institutional reforms, such as environmental legislation and market-based incentives to reduce environmental impacts"*. L'importance de la régulation et de sa nature a également été mise en avant avec le rapport sur le développement dans le monde de la World Bank (1992) qui précise que la croissance pourrait permettre d'atteindre un développement durable mais que *"tout dépendra des choix politiques qui auront été faits"*. Nous reviendrons sur le rôle central joué par les décideurs publics dans la relation environnement-croissance dans la section 0.3.2.

D'autres explications ont été mises en évidence. Une explication connue de la diminution des émissions de pollution accompagnant le développement est liée au commerce international et correspond plus précisément au déplacement des activités polluantes des économies développées vers des pays moins développés. Un tel déplacement pourrait provenir d'une régulation environnementale moindre dans les pays en développement, correspondant à la *Pollution Haven Hypothesis* (*cf.* Copeland & Taylor , 1994), ou d'une spécialisation due à des dotations en facteurs différentes. Dans les deux cas, la baisse de la pollution d'une économie ne serait alors qu'un report d'une économie vers l'autre et n'améliorerait pas l'environnement global.

Face à ce fait stylisé, diverses interprétations ont été faites. Beckerman (1992) conclut par exemple que *"in the end the best-and probably the only-way to attain a decent environment in most countries is to become rich"*. Certains auteurs vont jusqu'à argumenter que toutes politiques environnementales sont vaines et risquent même de nuire à l'environnement, en contraignant l'activité économique (*cf.* Barlett , 1994). Mais comme le rappellent Arrow *et al.* (1995): *"While [some papers] do indicate that economic growth may be associated with improvements in some environmental indicators, they imply neither that economic growth is sufficient to induce environmental improvement in general, nor that the environmental effects of growth may be ignored"*. Comme nous avons pu l'exposer précédemment, une telle relation n'est pas due seulement à une hausse de la richesse mais plutôt aux modifications qu'elle entraîne en termes de possibilités technologiques, de comportements (des ménages et des firmes) et de régulation.

Au delà du débat sur son interprétation, la courbe de Kuznets environnementale est également l'objet d'une discussion importante sur sa validité empirique. Des nombreux travaux empiriques cherchant à identifier pour quels polluants la CKE est vérifiée, il ressort qu'elle n'est valide que pour des polluants qui ont des effets locaux (SO_2, NO_X, CO, particules fines) alors que les polluants globaux comme le CO_2 entretiennent une relation monotone avec le revenu (*cf.* revue de la littérature de Dinda , 2004).

Deux limites additionnelles s'imposent au concept de courbe de Kuznets environnementale, dans le sens où elles rendent plus complexe le fait d'atteindre un développement durable. La première tient au caractère irréversible de certains dommages environnementaux, comme l'épuisement d'une ressource non-renouvelable, ou l'extinction d'espèces animales ou végétales. A partir de ce risque d'irréversibilité de la pollution, Dasgupta & Mäler (2002) s'opposent à l'idée que le développement est mécaniquement durable. Dans ce sens, Prieur (2009) montre dans un modèle similaire à celui de John & Pecchenino (1994) qu'un investissement en maintenance environnementale ne permet pas toujours d'atteindre la seconde phase de la CKE à partir du moment où la capacité d'absorption de la pollution est annihilée au delà d'un certain niveau de pollution. La deuxième limite de ce concept correspond au fait que la pollution a également des effets réciproques sur l'économie qui peuvent apparaître comme un frein au développement. Dans cette thèse, nous nous intéresserons surtout à ce second aspect, c'est à dire aux interactions réciproques entre les dimensions économiques et environnementales. Aussi, nous détaillerons les conséquences économiques des dommages environnementaux dans la section 0.2.2.

Nous pouvons donc conclure que le concept de courbe de Kuznets environnementale est à considérer avec prudence. A l'heure actuelle, il semblerait que les outils en faveur d'un développement durable soient insuffisants. Cependant, au vu des mécanismes identifiés et des améliorations observées à un niveau local dans les pays développés, un tel objectif est bel et bien envisageable sous réserve d'une modification suffisante des comportements de l'ensemble des agents économiques.

0.2.2 Effet de l'environnement sur l'économie

Après avoir mis en évidence les conséquences de l'activité économique sur l'environnement, il s'agit, dans cette section, de décrire comment la dégradation de l'environnement peut affecter en retour l'économie. Plusieurs canaux sont identifiés. En plus du rôle que l'environnement peut jouer en tant que facteur de production par le biais des ressources naturelles, la dégradation de l'environnement entraîne une perte de bien-être et porte atteinte à la santé de la population, comme le rappelle le rapport sur le développement dans le monde de la banque mondiale (World Bank , 1992). La pollution peut ainsi représenter un frein à la croissance économique. Dans cette section, nous chercherons à expliquer ces différents mécanismes et à identifier comment ils ont été pris en compte dans des modèles économiques.

L'environnement comme facteur de production

Certaines composantes de l'environnement peuvent être utilisées directement pour la production de biens et services. C'est le cas notamment de beaucoup de ressources naturelles comme l'eau, le bois, le fer, le pétrole, le charbon... Formellement, elles interviennent comme un *input* dans la fonction de production qui est utilisé en association avec d'autres facteurs (travail, capital physique, capital humain...) afin de produire un bien final. On distingue différents types de ressources en fonction de leur capacité à se régénérer et à s'épuiser. Tandis que les ressources non renouvelables (comme les ressources minérales) sont présentes naturellement en quantité limitée et présentent un risque d'épuisement très grand, d'autres ressources dites renouvelables ont la capacité de se renouveler. Au sein de ce deuxième groupe, les capacités de renouvellement sont variables. Certaines ressources (comme les ressources halieutiques ou forestières) sont susceptibles de disparaître si leur taux d'utilisation est supérieur à leur taux de renouvellement, alors que d'autres (comme l'énergie solaire et éolienne) ne sont pas affectées par leur utilisation. La plupart des ressources encourant un risque d'épuisement à plus ou moins long terme, la question de la durabilité du processus de développement se pose. Cette problématique a été soulevée dès Malthus (1798), Ricardo (1817) ou Jevons (1865), mais étudiée formellement beaucoup plus tard. Dasgupta & Heal (1979) résument la littérature théorique sur ce sujet et identifient les conditions sous lesquelles une croissance positive est possible. Ce résultat dépend de la nature du processus de production qui emploie ces ressources, et plus particulièrement du progrès technique, du caractère essentiel de ces ressources au processus de production, ou encore de la possibilité de les remplacer par des *backstop technologies* (technologies de substitution).[7] L'économie des ressources naturelles s'attache ainsi à étudier les modalités de prélèvement des ressources renouvelables et non-renouvelables afin d'évaluer, par exemple, à quel rythme nous devons utiliser des ressources qui sont épuisables (voir Rotillon , 2005 pour une revue de cette littérature).

Dans une perspective plus générale, l'économie de l'environnement étudie les problèmes liés à l'ensemble des dégradations environnementales causées par l'Homme et à ses interactions avec l'activité économique. C'est dans ce champ de recherche que s'inscrit cette thèse, aussi nous considérerons par la suite un indice de qualité environnementale multidimensionnel pouvant inclure la qualité de l'eau, de l'air, des sols, la biodiversité mais aussi l'état des ressources naturelles, sans étudier le rôle particulier des ressources naturelles dans le processus de production.

L'environnement comme source de bien-être

L'environnement possède également une valeur intrinsèque en tant que source d'aménités, c'est à dire de bien-être. Cette valeur est multiple. La qualité environnementale procure une valeur d'usage, correspondant à l'utilité apportée par son "utilisation". On peut penser, par exemple, à la qualité de vie associée à un environnement sain (air pur, eau de bonne qualité...), ou au bien-être procuré par certains loisirs liés directement à l'environnement (*e.g.* promenade en forêt). Elle a également une valeur de non usage, correspondant à une valeur d'existence ou encore à une valeur de legs. Ces deux concepts illustrent l'utilité que l'on peut retirer respectivement du fait de savoir que l'environnement est protégé (*e.g.* sauvegarde d'une espèce menacée) et du fait de léguer un bon environnement aux générations futures, motivé par l'altruisme dont les individus font preuve envers leurs enfants.

[7] Pour des contributions plus récentes traitant de la compatibilité entre croissance économique et ressources naturelles épuisables, voir par exemple Scholz & Ziemes (1999), Smulders & de Nooij (2003) ou Pérez-Barahona & Zou (2006).

Comme le rappellent Kany & Ragot (1998), Mill (1857) apparaît comme un précurseur de l'économie de l'environnement en considérant la qualité environnementale comme une source de bien-être plutôt que comme un simple facteur de production. Cependant, les études théoriques traditionnelles de la croissance ont par la suite négligé la présence de cet effet, jusqu'à la prise de conscience accrue des problèmes environnementaux des années 1970, à partir desquelles les travaux prennent enfin en compte la perte d'utilité due à la pollution, elle-même fruit de l'activité économique. Keeler *et al.* (1971) font justement partie des premiers à avoir formalisé cet effet de la pollution, qu'ils définissent comme *"any stock or flow of physical substances which impairs man's capacity to enjoy life"*.

De manière générale, les travaux en économie de l'environnement formalisent un indice de qualité environnementale qui est dégradé par l'activité économique (consommation ou production) et qui conduit à un gain d'utilité, ou alternativement un indice de pollution dû à l'activité économique et impliquant une perte d'utilité. Afin d'illustrer des formes répandues, nous représentons ici celle du papier fondateur de John & Pecchenino (1994), dont s'inspire beaucoup de contributions. Dans un modèle où l'utilité d'un individu dépend de sa consommation et de la qualité environnementale, les auteurs formalisent l'environnement comme un bien public de la forme:

$$Q_{t+1} = (1 - b)Q_t - \beta c_t + \gamma m_t$$

L'indice de qualité environnementale Q est donc représenté par un stock dégradé par la consommation des individus c_t et amélioré par un investissement en protection environnementale ou maintenance m_t. L'environnement se déprécie naturellement à un taux $b \in (0, 1)$, qui implique qu'il converge vers zéro en l'absence d'activité humaine. Cette définition renvoie à un indice de qualité environnementale qui est lié à la notion d'aménité, c'est à dire au bien-être que les individus en retirent. Cet indice multidimensionnel peut renvoyer, par exemple, à la qualité des sols, de l'eau ou de l'air, à la biodiversité ou à l'état des forêts et des parcs. Comme John & Pecchenino (1994) le précisent, la lutte contre la dégradation de certaines composantes de qualité environnementale n'est pas toujours possible (*e.g.* disparition d'espèces), mais elle l'est pour d'autres. Cette équation représente donc une approximation linéaire de la relation complexe qui peut exister entre la consommation, la dépollution et l'environnement. Un dernier élément à noter est que le flux net de pollution, c'est à dire consommation moins maintenance, agit avec une période de décalage sur le stock de qualité environnementale. Cette hypothèse représente le fait que les modifications de l'environnement naturel sont relativement lentes dans la réalité.

Cette équation de base peut ensuite être adaptée en fonction des questions posées. Par exemple, il pourra s'agir d'un indice de pollution plutôt que de qualité environnementale, d'un flux plutôt que d'un stock. La dégradation de l'environnement pourra être due à la production plutôt qu'à la consommation. La maintenance pourra être privée, publique, les deux ou ne pas exister du tout...

Pour illustrer un exemple avec pollution, nous pouvons considérer la forme adoptée par Michel & Rotillon (1995) qui étudient l'effet d'un stock de pollution sur le bien-être. Cette forme est équivalente à:

$$P_{t+1} = (1 - \mu)P_t + hY_t$$

La pollution est alors un mal public qui est un produit fatal de la production Y_t. Le coefficient $\mu \in (0, 1)$ représente la régénération naturelle de l'environnement, ce qui signifie que le stock de pollution aura une valeur autonome nulle, comme précédemment. Cet indice multidimensionnel pourra représenter ici l'opposé de la qualité environnementale décrite ci-dessus, illustrant par exemple la dégradation des sols, la pollution de l'air ou de l'eau, l'épuisement des ressources *etc.*

En affectant le bien-être des agents, la pollution peut modifier les choix des ménages (en termes de consommation, d'épargne, d'investissement en protection environnementale...) et modifier l'équilibre de l'économie. A partir des deux exemples ci-dessus, nous pouvons différencier deux cas. Dans le modèle de John & Pecchenino (1994), les agents affectent directement la pollution par le biais de leur consommation et de leur choix de maintenance environnementale. Lorsque leur niveau de vie augmente, leur consommation augmente également, de même que le flux de pollution. Cependant d'un autre côté, l'augmentation de leur revenu et la détérioration de leur bien-être engendrée par la hausse de la pollution, vont permettre aux ménages de pouvoir et de vouloir investir davantage dans des activités de maintenance. Dans ce cas, le développement n'est pas toujours associé à une augmentation de la pollution. Les agents se concentrent d'abord sur leurs besoins de consommation en dépit des effets sur l'environnement, puis au delà d'un certain niveau de vie et de pollution, ils commencent à investir de plus en plus dans la protection de l'environnement. John & Pecchenino (1994) retrouvent alors une relation en U inversé entre développement et pollution en accord avec la CKE. Au contraire, dans le modèle de Michel & Rotillon (1995), les agents ne peuvent investir en activité de dépollution et ne prennent pas en compte leurs effets sur la pollution. Par conséquent, bien que la pollution affecte le bien-être des agents, l'équilibre compétitif est le même qu'en l'absence de pollution et correspond à un processus de développement illimité associé à une augmentation illimitée de la pollution. Même lorsque la pollution exerce un effet de dégoût sur la consommation, qui renforce les effets négatifs de la pollution, les auteurs concluent à une croissance illimitée de la pollution, tandis que la solution optimale de l'économie correspond au contraire à un état stationnaire où la croissance de la production et de la pollution est nulle.

Dans cette thèse, nous considérerons une approche davantage reliée à celle de John & Pecchenino (1994), dans le sens où nous voulons tenir compte des comportements des ménages face à la pollution. Nous étudierons également des mécanismes additionnels reliant environnement et croissance, par le biais de préférences endogènes ou de la santé de ces individus, comme nous le détaillerons dans la suite de cette introduction.

Effet de la pollution sur la santé

Comme le rappelle l'organisation mondiale de la santé (OMS), *"The environment has always been crucial to sustaining human health and well-being, through the multiple benefits provided by ecosystems, clean air and safe drinking-water. The environment is a source of both health and disease and is an essential resource for the survival and development of people and societies"* (WHO , 2015a). Un autre canal essentiel par lequel l'environnement affecte l'économie est donc celui de la santé.

De très nombreuses études empiriques, notamment en épidémiologie, mettent ainsi en évidence des effets très importants de la pollution sur la santé. L'impact sanitaire de la pollution passe par la morbidité comme par la mortalité de la population, c'est à dire que la dégradation de l'environnement augmente à la fois le nombre d'individus atteints de maladies (non mortelles) et le nombre de décès. En particulier, les polluants atmosphériques (particules fines, monoxyde de carbonne, dioxyde de souffre, ozone *etc.*) sont identifiés comme des facteurs importants de risque sur la santé, notamment par leurs effets sur les systèmes respiratoire et cardiovasculaire des individus (voir par exemple Bell & Davis , 2001 ; Pope *et al.* , 2002 ; Bell *et al.* , 2004 ; Evans & Smith , 2005 ; Laurent *et al.* , 2007 ou Wilhelm *et al.* , 2009). Dans ce sens, l'OMS identifie que la pollution de l'air en 2012 était, à elle seule, responsable de plus de 7 millions de morts prématurées dans le monde, soit une mort sur huit (WHO , 2014). La pollution de l'air est ainsi devenue la forme de dégradation environnementale la plus dangereuse pour la santé, mais elle n'est pas la seule. Au niveau agrégé, l'OMS estime qu'environ un quart des maladies contractées par la population mondiale peut être attribué à des facteurs environnementaux (WHO , 2006), tandis que Pimentel *et al.* (1998) arrivent même à la conclusion que la pollution est à l'origine de près de 40% de la mortalité mondiale chaque année. La dégradation environnementale dans son ensemble a donc des conséquences majeures sur nos sociétés. Parmi les multiples formes que la pollution peut prendre, la pollution de l'eau, la contamination des sols, la raréfaction des ressources naturelles, le changement climatique et l'accumulation de déchets représentent également des risques importants sur la santé des individus (voir par exemple Valent *et al.* , 2004 ; Patz *et al.* , 2005 ou Zhao *et al.* , 2012). L'intensité de chacune de ces formes de pollution, de même que leurs conséquences en termes de santé, dépendront des caractéristiques de l'économie. La charge de mortalité et de morbidité impliquée par la pollution peut donc varier en fonction des pays. Les pays en développement sont les plus touchés par ce phénomène, principalement à cause de niveaux de pollution plus élevés mais aussi de moyens inférieurs, impliquant des difficultés d'accès aux soins, un manque de réglementation environnementale (contrôle de la qualité de l'eau, stockage des déchets *etc.*) et un manque d'informations sur les risques (WHO , 2006). Mais ce phénomène est global et touche chaque pays. S'agissant de l'Europe par exemple, l'OMS évalue en 2015 que *"malgré les progrès notables réalisés ces dernières décénnies en matière d'environnement et de santé, approximativement un quart de la morbidité et de la mortalité d'Europe est imputable à une exposition à des facteurs environnementaux"* (WHO , 2015a).

La dégradation environnementale a donc un coût humain plus que significatif, dont découlent des conséquences économiques importantes. Un rapport très récent de l'OMS estime que le coût annuel de la pollution de l'air en Europe est de plus de 1400 milliards d'euros par an (WHO , 2015b). Cette valeur correspond dans sa grande majorité (90%) au coût estimé des 600 000 décès prématurés observés chaque année à cause de la pollution, tandis que les 10% restants sont associés au coût des soins liés à la morbidité.[8] Ces montants représentent les coûts économiques relatifs aux soins et au temps perdu mais le fait que des individus soient malades ou meurent prématurément entraîne également

[8]Les montants relatifs à la mortalité sont évalués à partir de la *Value of Statistical Life* correspondant à un indice de consentement à payer pour diminuer le risque de mort prématurée. Voir WHO (2015b) pour le détail de la méthodologie.

une modification de leurs comportements, qui peut avoir des conséquences à court et à long terme. En particulier, la morbidité peut affecter l'offre de travail (arrêts maladies, absences dues à la santé des enfants...) et la productivité (problèmes de capacité, de concentration...). De nombreuses études empiriques mettent ainsi en évidence les effets de la pollution sur ces deux éléments (voir Ostro , 1983 ; Hubler *et al.* , 2008 ; Hanna & Olivia , 2011 or Graff Zivin & Neidell , 2012).

De même, par le biais de ses effets sur la mortalité, l'environnement peut influencer les choix individuels en modifiant leur rapport au futur. De nombreux papiers théoriques et empiriques montrent que l'allongement de l'espérance de vie pousse les agents à valoriser davantage le futur. Chakraborty (2004) propose un exemple assez intuitif de ce mécanisme, en identifiant que la hausse de la mortalité diminue les incitations à épargner, en augmentant l'impatience des individus qui ne pourront bénéficier de leurs investissements que pour une période réduite. Ce raisonnement s'applique également à la détermination des choix d'éducation. Le papier fondateur de Ben-Porath (1967) met ainsi en évidence qu'une plus grande longévité accroît les incitations à investir en capital humain, étant donné que cela permet aux agents de bénéficier du rendement de l'éducation pendant plus longtemps. L'effet positif de la réduction de la mortalité sur l'investissement en éducation a été testé et confirmé empiriquement par de nombreuses études, notamment par Miguel & Kremer (2004), Bleakley (2007), Jayachandran & Lleras-Muney (2009), Oster *et al.* (2013) ou Hansen (2013). Ce mécanisme a également été utilisé pour expliquer le processus de développement, notamment au sein de la théorie de la croissance unifiée. Ehrlich & Lui (1991), Boucekkine *et al.* (2003), Cervelatti & Sunde (2005) et Soares (2005) argumentent ainsi que l'allongement de l'espérance de vie favorise et renforce le processus de transition démographique ainsi que la croissance économique. S'agissant de l'éducation, il est à noter que la pollution agit également sur le processus d'apprentissage des enfants. En effet, par le biais d'absences répétées, de problèmes de concentration ou de détérioration des capacités cognitives, la pollution implique également une réduction de l'efficacité de l'éducation des enfants (voir par exemple Park *et al.* , 2002 ; Currie *et al.* , 2009 ou Facor-Litvak *et al.* , 2014 pour des études empiriques confirmant ces effets).

Par son impact sur la santé, la pollution s'avère ainsi avoir des conséquences majeures sur les comportements de court et de long terme. Toutes choses égales par ailleurs, en impliquant des coûts en temps et en biens, en dégradant les capacités de production et en désincitant les agents à épargner et à accumuler du capital humain, la pollution apparaît comme un frein à la croissance économique. Des contributions récentes ont donc analysé la relation environnement-croissance en prenant en compte la santé. Par exemple, Gutiérrez (2008) considère les coûts financiers impliqués par la dégradation de la santé à la retraite, Williams (2002) et Pautrel (2012) tiennent compte du coût en temps associé à la maladie diminuant ainsi l'offre de travail. van Ewijk & van Wijnbergen (1995) et Aloi & Tournemaine (2011) analysent l'effet de la pollution sur la productivité globale. Gradus & Smulders (1993) considèrent directement l'effet négatif de la pollution sur l'accumulation du capital humain. Enfin, une dernière catégorie d'articles se focalise sur la mesure la plus utilisée de la santé, à savoir la longévité. On peut citer notamment les contributions de Pautrel (2008), Jouvet *et al.* (2010), Mariani *et al.* (2010), Varvarigos (2010, 2011) ou Raffin & Seegmuller (2014). En plus du constat que la pollution peut avoir des effets négatifs sur la croissance et le développement par les différents canaux énoncés au début de ce paragraphe, ces contributions identifient un certain nombre de risques, tels que l'existence d'une trappe à pauvreté dans laquelle une économie peut être bloquée à long-teme (*cf.* Mariani *et al.* , 2010, Varvarigos , 2010 ou Raffin & Seegmuller , 2014), ou de volatilité de la croissance (*cf.* Varvarigos , 2011). En outre, étant donné le rôle renforcé de l'environnement dans le processus de croissance, ces contributions proposent également des politiques économiques et environnementales permettant de résoudre les problèmes identifiés. Dans ce sens, van Ewijk & van Wijnbergen (1995) concluent à la nécessité d'une politique environnementale pour assurer une croissance économique élevée.

Inégalités face aux effets de la pollution sur la santé

Une caractéristique fondamentale des effets de la pollution sur la santé est leur répartition inégale parmi la population. Si l'impact négatif de la dégradation environnementale sur la santé concerne tout le monde, ce problème est encore plus grand pour les individus n'ayant pas les moyens de s'en protéger. Comme on a pu l'énoncer précédemment, cette disparité en termes de vulnérabilité à la pollution est observée entre des pays plus ou moins développés et donc plus ou moins capables d'avoir un système de santé efficace (infrastructure, connaissances...), mais elle est également vérifiée au sein de chaque économie. Des disparités dans les effets de la pollution sur la santé sont ainsi observées entre des individus plus ou moins désavantagés d'un point de vue socio-économique. En particulier, des études empiriques identifient des différences dans les conséquences sanitaires des dommages environnementaux en fonction du niveau d'éducation des agents (voir par exemple Cifuentes *et al.* , 1999 ; Health Effects Institute , 2000 ; Pope *et al.* , 2002 ; O'Neill *et al.* , 2003 ou Cakmak *et al.* , 2011). Aux États-Unis, Zeka *et al.* (2006) identifient ainsi que le risque de mortalité associé aux particules fines PM_{10} des individus les moins éduqués est égal à plus de deux fois celui des individus les plus éduqués.[9] Les raisons mises en avant pour expliquer ces inégalités sont liées au fait que des individus plus éduqués ont tendance à vivre et à travailler dans de meilleures conditions, à bénéficier d'accès aux soins de santé plus faciles et à disposer de plus amples informations sur les problèmes environnementaux et sur les moyens de limiter leurs effets, ce qui leur permet d'adopter un mode de vie plus sain.

Ce résultat rejoint la littérature abondante étudiant l'impact de l'éducation sur la

[9] Cette étude porte sur vingt villes aux États-Unis entre 1989 et 2000. La catégorie des moins éduqués correspond à moins de 8 ans d'études (équivalent à un niveau inférieur au brevet des collèges en France), tandis que celle des plus éduqués représente plus de 12 ans d'études (équivalent à un niveau supérieur au baccalauréat en France).

santé, en dehors de considérations environnementales. De nombreuses contributions, comme celles de Elo & Preston (1996), Lleras-Muney (2005), Cutler & Lleras-Muney (2010) ou Miech *et al.* (2011), mettent ainsi en évidence le rôle de l'éducation sur la santé des individus, même après avoir contrôlé pour d'autres déterminants comme le revenu et l'emploi.[10] En dépit des progrès observés au niveau de l'espérance de vie moyenne, ces problèmes de disparités se sont accrus ces dernières décennies. Singh & Siahpush (2006) révèlent, par exemple, que l'écart de longévité entre les plus désavantagés et les moins désavantagés a augmenté de 60% entre 1980 et 2000 aux États-Unis. L'OCDE observe ainsi un écart d'espérance de vie de près de 8 ans entre les hommes les plus éduqués et les moins éduqués en moyenne en 2010 (OECD, 2013).

Comme nous avons pu le dire précédemment, les effets négatifs sur la santé peuvent avoir des conséquences très importantes au niveau macroéconomique. La répartition inégale de ces effets implique, de surcroît, qu'une partie de la population, qui est déjà désavantagée, risque de le devenir encore plus. Au niveau de l'ensemble de l'économie, le coût social en termes de bien-être et les coûts économiques engendrés par la modification du comportement et des capacités d'une partie de la population (possiblement très grande) expliquent pourquoi les inégalités en santé sont devenues une préoccupation politique majeure. Un grand nombre de ministères de la santé fait ainsi de la réduction de ces disparités un objectif prioritaire (voir par exemple U.S. Department of Health and Human Services , 2000 et U.K. Department of Health , 2003).

Il semble donc crucial de traiter de ces problèmes et de considérer que l'espérance de vie dépend à la fois de la pollution et du capital humain de chaque individu. Ce sera justement l'objet du troisième chapitre de cette thèse. Nous voulons comprendre les conséquences macroéconomiques de telles disparités et proposer des solutions en termes

[10]Contrairement à ce que l'on pourrait penser, l'éducation n'agit pas sur la santé que par le biais d'un effet revenu. Cutler & Lleras-Muney (2010) trouvent que les différences sont expliquées à 30% par les moyens financiers (assurance santé, revenu...), à 30% par les connaissances et les capacités cognitives et à 10% par un aspect réseau.

de politiques économiques pour les réduire. Bien que la mortalité soit la mesure de santé la plus analysée, aucune étude théorique n'a, pour l'heure, étudié les inégalités associées aux effets de la pollution sur la mortalité et de façon plus générale, très peu de travaux théoriques traitent de l'aspect inégalitaire des conséquences de l'environnement sur la santé. Aloi & Tournemaine (2013) et Schaefer (2014) représentent deux exceptions. Aloi & Tournemaine (2013) considèrent un effet direct de la pollution sur l'accumulation du capital humain, qui est inégalement réparti dans la population étant donné que les individus les moins éduqués sont davantage affectés. Dans ce contexte, la pollution a un effet direct sur les inégalités (positif) et sur la croissance (négatif car elle est conduite par le capital humain). Les auteurs mettent en évidence qu'une politique environnementale peut diminuer les inégalités et favoriser la croissance. Schaefer (2014) porte son attention sur la mortalité infantile. Il montre que la hausse de la mortalité infantile due à la pollution décourage les parents d'investir dans l'éducation de leurs enfants, ce qui diminue la croissance. Dans le chapitre 3, nous allons étudier l'espérance de vie et considérer, en accord avec les évidences empiriques, les effets de la pollution et du capital humain sur cette mesure de santé. Au contraire des deux articles ci-dessus, la vulnérabilité de chaque individu à la pollution va donc être amenée à évoluer avec le niveau de capital humain.

Dans cette partie, nous avons donc rappelé que l'environnement apparaît comme un déterminant majeur de l'activité économique, qui ne doit pas être négligé. Ainsi, dans cette thèse, nous chercherons à contribuer à une meilleure compréhension des interactions entre la sphère économique et la sphère environnementale et de l'importance de leurs implications. Pour cela, nous porterons notre attention sur le rôle particulier des ménages dans cette relation, qui semble central au regard des mécanismes énoncés dans les deux sens de cette relation. Nous détaillerons ce choix dans la section suivante.

0.3 Rôle des ménages et des décideurs publics dans la relation environnement croissance

0.3.1 Rôle des ménages

Les interactions entre les sphères économiques et environnementales accordent une place particulière aux ménages. Comme on a pu le mettre en évidence jusqu'à présent, les choix des agents sont cruciaux dans la détermination du volume et de la nature des émissions de pollution qui découleront de l'activité économique et, de façon réciproque, les effets de la dégradation de l'environnement sur le bien-être et la santé des individus vont façonner leurs comportements et ainsi définir les conséquences de la pollution sur le processus de développement. Dans cette section, nous allons détailler les caractéristiques des choix que peuvent effectuer les ménages, et présenter les outils adaptés à leur analyse.

Comportements verts

Comme l'indique le ministère français de l'écologie, du développement durable et de l'énergie: *"Chacun exerce dans sa vie quotidienne des pressions sur l'environnement : consommation alimentaire, d'eau, d'espace et d'énergie dans l'habitat et les transports... Ces pressions, qui paraissent négligeables à l'échelle de l'individu, peuvent avoir collectivement de forts impacts : pollution des eaux, de l'air, production de déchets... La demande des consommateurs pour des produits sains et peu polluants peut néanmoins susciter le développement d'une offre plus respectueuse de l'environnement."*.[11]

Par leurs décisions en termes de consommation, de fécondité, d'investissement en capital physique et humain, de legs ou de protection de l'environnement, les ménages affectent l'ensemble de l'économie et l'environnement à court et à long terme.

[11] Citation extraite du site du ministère: http://www.statistiques.developpement-durable.gouv.fr/environnement/s/pressions-impacts-menages.html.

S'agissant de l'environnement, tandis que les ménages influencent *a priori* positivement le volume des émissions de pollution et de production de déchêts par le biais de leurs choix en termes de consommation et de nombre d'enfants notamment, ils peuvent également participer à la protection de l'environnement. Les raisons motivant ces actions pro-environnementales tiennent au fait que les ménages valorisent l'environnement. Comme on a pu le voir, l'environnement a une valeur intrinsèque qui affecte leur bien-être. Dès lors, les individus arbitrent entre leurs activités polluantes et leur volonté d'assurer un certain niveau de qualité de vie, pour eux ou pour leurs enfants. Pour diminuer la pollution, plusieurs possibilités s'offrent à eux. D'abord, les agents peuvent simplement restreindre leur consommation de biens polluants. Ils peuvent également investir du temps ou de l'argent dans des activités dépolluantes (*e.g.* recyclage) ou payer un surcoût occasionné par la substitution de biens polluants par des biens de consommation dits verts, qui sont pas ou peu polluants mais caractérisés par des prix plus élevés.

Dans cette thèse, nous considérerons la présence d'arbitrages des ménages entre leurs activités économiques et l'environnement. Dans le chapitre 1, l'agent arbitrera entre sa consommation polluante et la qualité de l'environnement qu'il souhaite léguer à ses enfants. Dans le chapitre 2, l'individu pourra investir en maintenance environnementale privée, il arbitrera ainsi entre la consommation de bien privé et la protection du bien public. Les efforts de maintenance considérés représentent surtout des dépenses de dépollution et d'entretien de l'environnement, tel que le recyclage, les investissements en énergies renouvelables (panneaux solaires, géothermie...), l'installation des filtres, la plantation de végétaux, la protection d'espèces en voie d'extinction *etc.* Bien que nous ne formalisions pas ici des biens différenciés selon leurs effets sur l'environnement (biens verts, biens polluants), ils pourraient également illustrer le surcoût associé à la consommation de biens verts. Dans ce cas, une partie de la consommation totale, correspondant à la valeur de la maintenance, ne proviendrait donc pas de biens dont la production est polluante, ce qui diminuerait le flux de pollution.

Les contributions privées à la protection de l'environnement sont en accord avec les évidences empiriques. Kotchen & Moore (2008) concluent, par exemple, à l'existence d'un bénéfice psychologique et social associé à la participation à des programmes d'énergies vertes permettant de réduire les émissions de pollution, et ce en dehors du niveau de consommation d'énergie du ménage. Kotchen & Moore (2007) révèlent également que les préférences pour l'environnement et l'altruisme des individus sont des déterminants importants de la participation volontaire à ce type de programme. Ces évidences sont liées à une vaste littérature qui cherche à expliquer l'existence de contributions privées à des biens publics. Andreoni (1990) propose ainsi la formalisation d'un *altruisme impur* composé de deux motifs pour justifier les dons de charité. Plus précisément, ce type de comportement est alors dû à un altruisme *pur* pour la valeur finale du bien public et à un *warm glow joy of giving* qui représente le bien-être que l'agent retire directement de sa contribution à ce bien. Cela signifie que l'agent valorise l'effet de sa contribution sur le bien public mais aussi le simple fait de contribuer à ce bien. Une telle forme d'altruisme est supportée empiriquement s'agissant de la donation (voir *e.g.* Ribar & Wilhelm , 2002 ou Crumpler & Grossman , 2008) mais également s'agissant des contributions privées à la protection de l'environnement (*e.g.* Menges *et al.* , 2005). De plus, cette forme guarantie que les protections environnementales privées et publiques ne sont pas parfaitement substituables, et permet donc de se placer dans un cadre où le résultat très controversé de neutralité totale de la politique environnementale est absent. Dans le chapitre 2, nous traiterons de l'efficacité de politiques environnementales lorsque la motivation des ménages à investir dans des activités de maintenance environnementale est endogène. Nous considérerons donc que l'investissement en maintenance privée est motivé par la qualité de l'environnement et par le fait de participer à la protection de l'environnement.

Évolutions des préférences environnementales

Les préférences environnementales des agents déterminent à quel point la détérioration de l'environnement affecte leur bien-être et comment ils y réagissent en retour. La littérature empirique révèle que ces préférences évoluent dans le temps. La Commission Européenne identifie ainsi qu'au cours des dernières décennies, les ménages ont pris de plus en plus conscience à la fois des problèmes environnementaux et du rôle qu'ils peuvent jouer dans la protection de l'environnement (European Commission , 2008). De façon plus précise, Dunlap & Scarce (1991) rappellent que si les préférences pour l'environnement ont augmenté depuis les années 60, elles ont fluctué en fonction du contexte économique et environnemental. Typiquement, une augmentation des problèmes environnementaux a tendance à augmenter leur soutien à la protection de l'environnement, alors qu'une dégradation des conditions économiques décourage les comportements verts. Scruggs & Benegal (2012) mettent ainsi en exergue que le déclin des préoccupations des américains pour le changement climatique observé depuis 2008 est dû à la situation économique.

Le mécanisme par lequel l'état de l'environnement affecte les préférences vertes est plutôt intuitif. En effet, lorsque les individus perçoivent que les dommages environnementaux sont importants, ils sont davantage susceptibles de prendre conscience de l'ampleur du problème, et d'être affectés négativement par cette pollution, ce qui les incite à réagir. S'agissant du contexte économique, on peut imaginer qu'il s'agit d'un problème de priorités. L'environnement apparaissant généralement comme un problème de long terme, lorsque la situation économique est mauvaise, les agents se focalisent sur leurs besoins de court terme, et se soucient moins des problèmes environnementaux. Dans ce sens, Gubler (2003) soutient, par exemple, que lorsque le chômage augmente dans l'économie, les ménages accordent une importance moindre à la protection de l'environnement. De surcroît, de nombreuses études mettent également en évidence le rôle des connaissances sur les préférences environnementales individuelles. Par exemple, les travaux de Blomquist & Whitehead (1998), Witzke & Urfei (2001), Franzen & Meyer (2010) ou encore ceux de la commission européenne (European Commission , 2008) montrent que des agents plus éduqués consentent davantage à payer pour protéger l'environnement. Une telle différence s'explique notamment par le fait que des personnes plus éduquées sont susceptibles de bénéficier de plus amples informations sur les problèmes de pollution et leurs conséquences, ce qui favorise la prise de conscience des enjeux environnementaux.

Étant donné que les préférences environnementales déterminent la sensibilité des agents à l'environnement, la prise en compte de leurs évolutions a des implications importantes sur le comportement des ménages et donc sur l'économie. Certaines contributions ont analysé les conséquences d'un changement de préférences environnementales incertain sur la trajectoire optimale de l'économie. Beltratti *et al.* (1998) et Ayong Le Kama & Schubert (2006) trouvent notamment que lorsque l'on anticipe des préférences environnementales supérieures pour les générations futures, il est optimal de conserver davantage l'environnement dès maintenant. Ayong Le Kama & Schubert (2004) montrent cependant qu'un tel résultat dépend des caractéristiques de l'économie et n'est donc pas toujours obtenu. Bien que ces contributions tiennent compte de l'évolution possible des préférences dans le temps, elles n'intègrent pas les déterminants expliquant ces évolutions. À notre connaissance, seuls deux articles considèrent pour l'instant les implications macroéconomiques de préférences environnementales endogènes. Prieur & Bréchet (2013) formalisent l'effet de l'éducation sur ces préférences, définies comme l'élasticité entre consommation et qualité environnementale future. Dans un contexte où l'éducation est entièrement publique, les auteurs identifient que l'éducation ne favorise pas nécessairement un processus de croissance soutenue et soutenable. En effet, lorsque les agents accumulent des connaissances, ils investissent davantage en maintenance environnementale, au détriment de l'épargne et de l'accumulation de capital physique.

Aussi, l'effet de l'éducation sur les préférences peut impliquer que l'économie ne convergera pas vers un sentier de croissance équilibrée, mais plutôt vers un état stationnaire. Prieur & Bréchet (2013) montrent cependant qu'il est possible de maintenir un processus de croissance à long terme pour certains niveaux de taxe finançant l'éducation publique. Schumacher & Zou (2013) prennent en compte l'effet de la pollution courante sur les préférences pour l'environnement futur, à l'aide d'effets de seuils.[12] En comparant plusieurs niveaux de seuils possibles, les auteurs soulignent que la valeur du seuil détermine la qualité environnementale vers laquelle l'économie converge et comment elle l'atteint. Si le seuil d'environnement au dessous duquel les agents se préoccupent du problème environmental est faible, alors l'économie convergera à long terme vers un environnement très dégradé en dépit de la modification des comportements, tandis que si ce seuil est élevé, l'économie convergera vers un environnement faiblement dégradé à long terme. Pour des seuils intermédiaires, Schumacher & Zou (2013) soulignent l'existence d'inégalités intergénérationnelles générée par le fait que l'économie oscille indéfiniment entre maintenance très faible et très élevée. Si la qualité environnementale est bonne, les agents ne s'en soucient pas jusqu'à ce que l'environnement soit inférieur au seuil limite, alors qu'une fois ce seuil franchi, ils investissent beaucoup en protection de l'environnement jusqu'à ce que l'environnement soit suffisamment bon, et qu'ils recommencent alors à polluer *etc.*

Dans le chapitre 2, nous porterons notre attention sur le fait que les préférences pour l'environnement soient endogènes. Plus précisément, nous étendrons les travaux de Prieur & Bréchet (2013) et Schumacher & Zou (2013) en considérant deux déterminants de ces préférences identifiés empiriquement, à savoir le capital humain et la pollution.[13] Nous supposerons que ces deux variables agissent de manière continue sur les préférences, en accord avec les évidences énoncées précédemment qui indiquaient que malgré la prise

[12] Le fait de franchir ces seuils n'est pas irréversible.

[13] Dans le modèle, le capital humain pourra capter à la fois le niveau de connaissances et de revenus de l'individu (sa situation économique).

de conscience des ménages depuis les années 60, ces préférences continuaient d'évoluer. C'est l'interaction entre le niveau de pollution, qui affecte les agents, et leurs connaissances, qui leur permettent d'identifier le problème et d'avoir les moyens d'agir, qui déterminera l'effort qu'ils sont prêts à entreprendre pour protéger l'environnement. De plus, nous considérerons les choix privés en termes d'éducation, de sorte qu'il y ait un arbitrage entre l'éducation que les ménages souhaitent prodiguer à leurs enfants et le niveau de qualité environnementale qu'ils souhaitent leur léguer.

Dimension intergénérationnelle des choix des ménages: modèles à générations imbriquées

La plupart des choix qu'effectuent les ménages ont une dimension intergénérationnelle, volontaire ou non. Par exemple, lorsque des parents financent l'éducation de leurs enfants, ou leur lèguent volontairement quelque chose, ils cherchent directement à aider la génération suivante par le biais de transferts intergénérationnels. Mais les choix des ménages peuvent également avoir des effets involontaires sur les générations suivantes, notamment par le biais de l'environnement (en consommant des biens polluants par exemple). Ces externalités intergénérationnelles proviennent du fait que les décisions d'agents à durée de vie finie peuvent avoir un impact sur des variables à horizon plus lointain. En dégradant l'environnement et en participant à l'épuisement des ressources, les générations présentes sont ainsi à l'origine de conséquences importantes pour les générations à venir. La dimension intergénérationnelle est donc au cœur des problèmes environnementaux et il semble crucial de la considérer dans nos analyses.[14] Les modèles à générations imbriquées, introduits par Allais (1947) puis développés par Samuelson (1958) et Diamond (1965), représentent un outil privilégié pour cela.[15] Contrairement

[14] Son importance est également rappelée par la célèbre définition du développement durable donnée par la commission Brundland, que l'on a énoncé précédemment (WCED , 1987).

[15] Voir de la Croix & Michel (2002) pour une revue des modèles à générations imbriquées et de leurs implications.

aux modèles à agents représentatifs dont la durée de vie est infinie, ils ne restreignent pas l'analyse à des problèmes intragénérationnels, c'est à dire au sein d'une génération. Dans les modèles à générations imbriquées, les individus sont mortels, leurs choix peuvent donc avoir des conséquences qui leur survivent et dont ils ne tiennent pas compte, ou uniquement partiellement, comme c'est le cas dans la réalité. Le cycle de vie est scindé en deux ou trois périodes de vie, représentant par exemple l'enfance, l'age adulte et la retraite, et plusieurs générations, dont les arbitrages diffèrent, co-existent. Ils permettent donc d'étudier à la fois les questions intra- et inter-générationnelles. Pour ces raisons, ils sont utilisés dans de nombreuses contributions pour traiter de problèmes environnementaux, depuis les travaux fondateurs de Howarth & Norgaard (1992), Michel (1993) ou John & Pecchenino (1994).[16] Ces modèles étant parfaitement adaptés à l'analyse des conséquences des choix des ménages sur les sphères économique et environnementale que nous souhaitons effectuer, nous adopterons donc cette structure dans chacun des chapitres de cette thèse.

L'altruisme, au centre des décisions

Bien que certains choix individuels, comme la consommation, soient effectués par égoïsme pur, d'autres sont motivés par de l'altruisme. En particulier, un type très fréquent d'altruisme est celui dont les parents font preuve à l'égard de leurs enfants. Becker (1991) rappelle ainsi que: *"Yet many economists dispute that altruism is important in families, even though these same economists often deny themselves in order to accumulate gifts and bequests for their children. Moreover, parental love, especially mother love, has been recognized since biblical times"*. Il existe plusieurs formes d'altruisme. La plus utilisée est l'altruisme dynastique *à la* Barro (1974) où l'utilité des enfants entre di-

[16] Les agents n'étant pas capables de tenir compte des conséquences de leurs actions à long terme, ces papiers mettent en évidence le caractère non-optimal de l'équilibre concurrentiel (possible d'augmenter le bien-être d'une génération sans détériorer le bien-être d'une autre). Ils évaluent également les politiques économiques et/ou environnementale à implémenter pour décentraliser l'optimum. Voir Fodha (1998) pour une analyse comparative de ces trois contributions.

rectement dans celle des parents. Cette hypothèse suppose donc que les parents intègrent parfaitement les préférences de leurs enfants aux leurs et implique que la famille se comporte comme une dynastie, équivalente à un agent à durée de vie infinie. Intuitivement, il paraît difficilement imaginable qu'un individu soit capable d'anticiper parfaitement toutes les sources de bien-être de ses enfants. Aussi, les évidences empiriques remettent en cause le réalisme de cette hypothèse (*e.g.* Altonji *et al.* , 1992).

De façon alternative, une autre forme d'altruisme dite paternaliste correspond au fait que l'agent altruiste se préoccupe d'un ou plusieurs élément(s) particulier(s) consommé(s) par le bénéficiaire, en dehors du bien-être que celui-ci en retire. Cette forme est supportée empiriquement par Jacobsson *et al.* (2007), par exemple, qui concluent que c'est l'altruisme paternaliste qui motive principalement les dons en santé. Au sein d'une structure familiale, cette empathie imparfaite correspond à la vision que les parents ont de ce qui est bon pour leurs enfants et au plaisir associé au fait de donner (composante *warm glow joy of giving* à la Andreoni , 1990). Pour illustrer l'idée que les parents ne valorisent pas les préférences de leurs enfants mais plutôt certains éléments qu'ils pensent être bons pour eux, Pollak (1988) donne l'exemple de parents qui acceptent de donner de l'argent à leurs enfants pour leurs études ou pour les aider à payer un prêt immobilier, mais pas pour qu'ils achètent un bien que le parent juge futile (en l'occurrence une mercedes). En considérant les deux composantes de l'altruisme paternaliste, ce motif peut donc s'appliquer, par exemple, au capital humain que les parents souhaitent pour leurs enfants, au legs économique qu'ils veulent leur laisser ou à la qualité environnementale qu'ils veulent leur transmettre (legs environnemental). Dans cette thèse, nous considérerons ces trois motifs d'altruisme. On peut également noter que ces motifs d'altruisme paternaliste sont très proches d'une troisième forme d'altruisme, dite familiale (*cf.* Lambrecht *et al.* , 2005). L'altruisme familial suppose que les parents se soucient de la richesse totale de leurs enfants, c'est à dire du legs économique qu'ils reçoivent et de leurs revenus futurs. Comme pour l'altruisme paternaliste que nous considérons, les choix sont faits au sein d'une famille et ne dépendent pas de l'utilité totale des enfants. De plus, la valeur du capital humain des enfants est proche de la valeur de leurs revenus futurs. Cependant, les motifs qui participent à la richesse que nous considérons sont plus faciles à évaluer pour les parents (éducation ou legs) et nous nous intéressons également à des motifs qui ne sont pas liés à la richesse, comme le legs environnemental.

L'altruisme sera au cœur des arbitrages effectués par les agents et pourra ainsi influencer la dynamique de l'environnement, l'accumulation du capital physique et celle du capital humain. Ce concept sera donc au centre de notre analyse des interactions entre environnement et croissance.

0.3.2 Rôle des décideurs publics

Étant donnés l'ampleur des problèmes environnementaux et les effets de la pollution sur l'économie par le biais du processus de production mais surtout du bien-être et de la santé des individus, la mise en place de politiques pour diminuer la pollution apparaît comme une nécessité. Dans une approche plus économique, le besoin de politiques environnementales vient notamment du fait que l'environnement soit un bien public, ce qui incite les agents à sous-investir dans sa protection (problème de passager clandestin notamment), et qu'il représente une source d'externalités. Comme on a pu en donner l'intuition précédemment, les externalités viennent du fait que les agents ne tiennent pas compte du caractère dommageable de leurs actions sur autrui, ici par le biais de la pollution. Le propre de ces externalités est que malgré les conséquences importantes qu'elles peuvent impliquer sur la société (présente et future), elles ne sont pas prises en compte par le marché et ne sont pas compensées, d'où l'importance du rôle du décideur public. La question est ensuite de savoir si cette politique se fait au détriment du développement économique, ou si au contraire, elle peut permettre de renforcer la croissance, en neutralisant les effets négatifs sur l'économie. Dans cette section, nous allons essayer d'identifier les politiques environnementales possibles et leurs implications.

Outils de politiques environnementales

Pour diminuer la pollution, les décideurs publics peuvent mettre en place des mesures réglementaires (normes) ou implémenter des instruments économiques.[17] Si les normes sont les outils les plus souvent utilisés, elles sont jugées peu efficaces.[18] Au contraire, les instruments économiques sont valorisés pour leur caractère incitatif. Ils permettent ainsi de modifier les comportements des agents de manière durable, en les incitant à diminuer leurs émissions de pollution et à chercher des solutions alternatives (*e.g.* développement de technologies vertes ou modification du type de biens consommés). Deux grandes catégories d'instruments économiques existent pour diminuer les émissions de pollution: des régulations par les quantités (quotas de permis à polluer) et des régulations par les prix (taxes, subventions). La deuxième catégorie, et plus particulièrement la taxe sur les activités polluantes, est souvent privilégiée pour sa transparence et son absence de volatilité (prix fixé et donc non volatile, à l'inverse des permis d'émission échangeables). Elle présente également l'avantage de fournir un revenu à l'État qu'il peut ensuite recycler. Cette recette fiscale peut, en effet, être utilisée pour diminuer des déficits publics, pour redistribuer un revenu aux ménages, pour financer des dépenses de protection environnementale ou pour diminuer d'autres taxes. Cette dernière possibilité est l'objet de la littérature sur le double dividende qui identifie qu'une taxe sur la pollution dont le revenu serait utilisé pour diminuer d'autres impôts plus distordants permettrait ainsi d'obtenir un dividende environnemental et un dividende économique (voir Goulder , 1995 ; Chiroleu-Assouline & Fodha , 2006).[19] Schubert (2009) préfère l'option d'accorder ce

[17] Voir Beaumais & Chiroleu-Assouline (2002) ou Schubert (2009) pour une analyse détaillée de ces outils.

[18] Le niveau optimal de pollution auquel doit être fixée la norme étant très difficile à évaluer dans la réalité, elle aura très peu de chance d'être optimale. De plus, les normes n'ont pas de caractère incitatif ou flexible, ce qui limite fortement leur efficacité.

[19] Un impôt est distordant si son rendement pour l'état est inférieur au coût qu'il engendre pour le contribuable.

revenu aux ménages de façon forfaitaire, en argumentant que les entreprises répercutent le côut de la taxe sur leurs prix. Dans cette thèse, nous utiliserons une taxe sur les activités polluantes dont le revenu sera recyclé en protection environnementale directe ou indirecte.

Par politique environnementale indirecte, nous faisons référence à la position des organisations internationales sur le rôle des politiques éducatives pour atteindre des objectifs environnementaux. Dans ce sens, les Nations Unies ont déclaré la décénnie 2005-2014 comme celle de l'éducation pour le développement durable, tandis que l'OCDE met en avant que: *"Education is one of the most powerful tools for providing individuals with the appropriate skills and competencies to become sustainable consumers"*. L'intuition sous-jacente à cette position repose sur l'influence que le capital humain peut avoir sur les préférences environnementales. Comme on l'a énoncé précédemment, le capital humain est effectivement identifié comme un déterminant important de la sensibilité des individus aux questions environnementales. Un tel outil est également promu car il permettrait de favoriser à la fois les consciences vertes et le développement économique. Le deuxième chapitre sera consacré à l'analyse d'une politique environnementale combinant des outils classiques de politiques environnementales, à savoir la taxe sur les activités polluantes et l'investissement de l'État en maintenance environnementale, et cet outil particulier qui vise à influencer les comportements individuels. Nous étudierons alors les conséquences de ce type de *policy mix* en fonction de l'allocation choisie entre les deux dépenses publiques, c'est à dire en fonction de si le revenu de la taxe est dévoué uniquement à l'éducation ou à la maintenance environnementale ou s'il est alloué au deux.

Dans le troisième chapitre, nous nous intéresserons également au rôle d'une politique environnementale mais dans un cadre différent relatif aux inégalités en santé. Afin d'évaluer si une politique environnementale est capable de diminuer ce type d'inégalités, nous préférons nous concentrer sur une politique purement environnementale, c'est à dire composée d'une taxe sur la pollution et d'une protection publique de l'environnement.

Politique environnementale et croissance de long-terme

La politique environnementale est souvent perçue comme quelque chose qui contraint la croissance, mais ce n'est pas forcément le cas. Au contraire, certaines contributions trouvent qu'elle peut la favoriser, voire même en être une condition nécessaire, lorsque l'on prend en compte les effets négatifs que les dommages environnementaux engendrent sur l'économie. Différents canaux de transmission peuvent expliquer qu'une politique environnementale, qui réduit la pollution, peut affecter positivement la croissance.[20] Par exemple, chez Gradus & Smulders (1993), van Ewijk & van Wijnbergen (1995) ou Bovenberg & Smulders (1996), cela est dû à la neutralisation des effets négatifs de la pollution sur les capacités d'apprentissage des enfants ou sur la productivité, tandis que chez Grimaud & Tournemaine (2007) et Pautrel (2014), cela s'explique par le fait que la politique défavorise un secteur polluant au profit d'un deuxième secteur non polluant et intensif en capital humain (de recherche ou de dépollution), qui est le moteur de la croissance économique. Cependant, la prise en compte des effets négatifs de l'environnement sur l'économie n'aboutit pas toujours à cette conclusion, notamment lorsqu'ils agissent par le biais de l'espérance de vie (voir par exemple Raffin & Seegmuller, 2014).

[20]Voir Ricci (2007) pour une revue des mécanismes identifiés dans la littérature.

0.4 Présentation de la thèse

Cette thèse est consacrée à l'étude macroéconomique du lien entre croissance et environnement et au rôle des comportements des ménages dans cette relation, en particulier lorsqu'ils sont guidés par de l'altruisme pour leurs enfants. Nous chercherons à compléter la compréhension théorique des interactions entre les sphères économique et environnementale mais aussi à prodiguer des recommandations politiques afin de solutionner les impacts négatifs pouvant en émaner.

Au sein de cette problèmatique générale, nous allons nous pencher sur des questions particulières dont l'étude semble importante au regard de ce que nous avons pu mettre en évidence dans l'introduction et qui restent pour l'heure inexplorées. Nous nous demandons ainsi: Comment les décisions des ménages ont-elles contribué au processus d'industrialisation, qui est lui-même à l'origine d'un accroissement considérable de la pollution? Quelles sont les conséquences macroéconomiques du fait que les ménages aient des préférences environnementales qui évoluent en fonction de leurs connaissances et de la pollution qu'ils subissent, et quel rôle une politique environnementale cherchant à affecter ces préférences peut jouer sur l'économie? Comment les décisions des individus peuvent être impactées par les effets de la pollution sur la santé et quelles implications cela entraîne sur l'économie et sur le rôle des politiques environnementales? Ce sont donc les questions auxquelles nous nous attacherons à répondre dans cette thèse.

0.4.1 Chapitre 1 : Croissance de la population dans une industrialisation polluante

Dans ce premier chapitre, l'objectif est de comprendre la relation de long terme entre le développement et l'environnement et d'analyser le rôle que peuvent jouer les comportements des ménages dans les premiers stades de développement. Comme nous l'avons souligné au début de cette introduction, la révolution industrielle marque un tournant majeur pour le processus de développement et pour ses conséquences sur l'environnement, aboutissant même à une nouvelle ère géologique. Il s'agit ici d'évaluer le rôle que peuvent jouer les choix des ménages dans ces modifications.

Pour cela, nous formalisons un modèle à générations imbriquées où les ménages choisissent leur niveau de consommation, mais aussi le nombre d'enfants qu'ils désirent ainsi que les legs économique et environnemental qu'ils veulent laisser à leurs enfants. Le choix de qualité environnementale que le parent lègue à son enfant est conditionné par l'état de développement espéré. Plus précisément, les individus arbitrent entre la qualité de l'environnement et la richesse familiale qu'ils souhaitent pour eux. Cet arbitrage correspond à l'idée que *"dans les premières étapes de développement, une augmentation de la pollution est considérée comme un effet secondaire acceptable de la croissance économique"*, comme le soulignent Arrow *et al.* (1995) par exemple. Ainsi, lorsque la prospérité familiale attendue est grande, les agents consentent à laisser un environement plus dégradé à leurs enfants. De plus, les individus approximent cette richesse future de la famille par la taille de la famille, étant donnée l'étroite relation entre ces deux variables pendant le régime malthusien et post-malthusien que nous étudions ici.

S'agissant de la pollution, elle correspond à un stock provenant de la consommation, de sorte que les ménages prennent en compte leurs effets et arbitrent entre leur consommation et l'environnement. Comme nous nous focalisons sur les premières étapes de développement, cet indice multi-dimentionnel illustre plusieurs éléments évoluant avec le développement. Dans l'ère pré-industrielle, il correspond surtout à une définition agraire, comme par exemple l'état de ressources naturelles ou la qualité des terrains. Il représente ensuite, au fur et à mesure du processus de développement, une pollution davantage liée à une production industrielle, comme la pollution de l'eau ou de l'air et relative à la détérioration des conditions sanitaires dans les villes.

Dans ce contexte, nous montrons qu'il existe plusieurs équilibres de long-terme: un équilibre pré-industriel correspondant à une trappe à pauvreté et un équilibre industriel. Ce second état est caractérisé par un développement plus important, une croissance de la population plus grande mais aussi par un environnement bien plus dégradé. La trappe à pauvreté se réfère donc ici à un état où l'environnement est faiblement pollué mais où l'économie est bloquée à un stade de développement pré-industriel dont les conditions économiques, bien que mauvaises, peuvent encore se dégrader. Dans notre modèle, la croissance de la population apparaît comme un déterminant majeur du processus d'industrialisation. Au contraire des résultats de Nelson (1956) par exemple, une fécondité endogène n'est pas responsable d'une trappe à sous-développement mais au contraire est une condition du développement. Pour une même dotation initiale en capital physique, une économie dont la fécondité est faible peut rester dans un état de développement pré-industriel, tandis qu'une autre dont la fécondité est grande pourra expérimenter le processus d'industrialisation. Ce résultat fait sens au regard du fait que le processus de production a besoin d'une main d'oeuvre très abondante au début de l'industrialisation. Par ailleurs, l'environnement occupe également une place importante dans l'existence de la trappe à pauvreté. En effet, si la pollution ne persistait pas dans le temps, un tel état de long terme n'existerait pas et l'économie convergerait toujours, à terme, vers un état industriel. Les interactions entre les sphères démographique et environnementale sont donc au coeur de ces résultats.

Nous mettons également en évidence qu'une économie piégée dans la trappe à pauvreté peut toujours en sortir à l'aide d'un choc technologique suffisamment grand, en accord avec la théorie du "Big Push" ; cependant la taille du choc requis est très variable en fonction de la situation initiale de l'économie. Ce choc peut représenter une innovation technologique majeure dans ce pays ou surtout un transfert de technologie en provenance d'autres pays (volontaire ou non), qui semble avoir eu une importance particulière dans le déclenchement de la révolution industrielle des différents pays. Ce résultat est en accord avec le fait que la majeure partie des pays ait connu ce processus d'industrialisation mais à des dates pouvant être très différentes. Nous retrouvons ainsi l'existence d'une polarisation de l'économie mondiale et d'un possible accroissement des inégalités entre pays.

Nous développons donc, dans ce chapitre, un modèle théorique simple permettant de donner une explication du processus d'industrialisation et de ses conséquences en termes de pollution par l'intermédiaire des comportements démographiques et environnementaux des ménages.

Alors que, dans le premier chapitre, nous centrons notre attention sur l'analyse du lien croissance-environnement dans les premiers stades de développement, les chapitres 2 et 3 sont consacrés à l'étude de ce lien au sein d'économies développées. Ce changement de cadre nous amène à modifier la structure du modèle à générations imbriquées que nous utilisons. Au vu du fait que les choix de fécondité soient stabilisés dans les pays développés, nous prenons notamment le parti de considérer dans ces chapitres la population comme constante afin de nous focaliser sur d'autres mécanismes. De même, en portant notre attention sur des pays développés, il semble crucial de prendre en compte le capital humain qui occupe une place majeure dans le régime d'économie moderne, comme on a pu le mettre en évidence dans la Section 0.2.1 de cette introduction. S'agissant des effets que le capital humain entraîne sur l'environnement, nous considérons dans ces deux chapitres que les émissions de pollution sont dues à la production totale. Si le capital humain n'est pas un facteur de production polluant en soi, il est utilisé en association avec des facteurs intenses en pollution (comme le capital physique) et participe à définir les volumes de production et de pollution.[21] Dans la réalité, le capital humain contribue aussi au verdissement de l'économie, étant donné que les secteurs de production les plus intensifs en capital humain sont souvent les moins polluants et qu'il permet le développement de technologies vertes. Ici, nous prenons en compte les effets positifs du capital humain sur l'environnement par le biais de la maintenance environnementale.

[21] On peut remarquer qu'en formalisant une pollution provenant de la consommation, le capital humain aurait également contribué à la dégradation de l'environnement par le biais d'un effet revenu (augmentant le volume consommé).

Une hausse du capital humain augmente ainsi le volume de la pollution, mais également les dépenses de protection environnementale (privées ou publiques).

0.4.2 Chapitre 2 : Politique environnementale et croissance lorsque la conscience environnementale est endogène

Dans ce second chapitre, nous nous intéressons aux effets d'une *policy mix* implémentée pour atteindre des objectifs environnementaux. Plus précisément, nous considérons un schéma de politique environnementale composé d'outils classiques, tels qu'une taxe sur la pollution et une protection environnementale publique, mais aussi d'une politique éducative mise en place afin de modifier les comportements des agents vis à vis de l'environnement. Si ce dernier outil ne correspond pas à une vraie politique environnementale, il est présenté comme un moyen privilégié pour atteindre un développement durable par les organisations internationales, étant donné que l'éducation s'avère avoir des conséquences importantes sur les préférences environnementales des agents, tout en bénéficiant aussi au processus de développement. Il s'agit ainsi, dans ce chapitre, d'évaluer les effets d'une politique environnementale, pouvant combiner ces outils directs et indirects, sur l'économie et sur la croissance plus spécifiquement.

Afin d'étudier ce type de politiques, il semble indispensable de prendre en compte l'endogénéité des consciences environnementales des individus. D'abord, nous considérons que ces préférences dépendent du niveau de capital humain des agents, en accord avec les évidences empiriques exposées précédemment. Cette relation s'explique notamment par le fait que des individus plus éduqués ont tendance à bénéficier de plus amples informations sur les problèmes environnementaux et leurs conséquences et donc à être davantage conscients de ces problèmes. Nous tenons également compte d'un deuxième déterminant de ces préférences, identifié empiriquement, qui est le niveau de la pollution. En affectant le bien-être et la santé des agents, la pollution semble apparaître comme un signal d'alarme qui pousse les individus à réaliser l'étendue du problème et ses conséquences. À capital humain donné, la pollution incite donc à réagir et augmente les préférences vertes.

Nous formalisons un modèle à générations imbriquées, où les parents se préoccupent du capital humain de leurs enfants, de sorte qu'ils financent leur éducation, et de la qualité environnementale qu'ils leur lèguent. La conscience environnementale endogène correspond au poids des composantes environnementales dans la fonction de bien-être des individus, c'est à dire au poids de ce legs environnemental mais aussi du simple fait de contribuer à la protection de l'environnement (*joy of giving*). Comme on a pu le mettre en avant précédemment, la maintenance environnementale, qui est une contribution privée à un bien public, s'explique par de l'altruisme impur à la Andreoni (1990). Nous adoptons cette forme car, en plus d'être soutenue empiriquement, elle nous permet d'être dans un cadre où l'effet d'éviction entre maintenances privée et publique n'est pas total, ce qui nous permet d'étudier un schéma politique avec protection environnementale publique. En accord avec ce que nous avons énoncé, la politique sera composée d'une taxe sur la production polluante, dont le revenu peut être recyclé en maintenance environnementale publique et/ou en subvention à l'éducation. Ce dernier outil, implémenté pour favoriser les préférences vertes, a donc un effet positif sur l'environnement, en incitant les individus à protéger l'environnement et en leur donnant davantage de moyens pour le faire (par un effet revenu), mais il a également un effet négatif sur l'environnement en participant à la production et en définissant son volume.

Cette structure, résumée dans le schéma 2, nous permet de trouver qu'il existe un unique équilibre de long terme qui est caractérisé par un développement durable, où le capital humain et la qualité environnementale croissent. Ce résultat est obtenu sous certaines conditions, dont notamment que les activités de maintenance doivent être suffisamment efficaces. De plus, il convient de préciser que la qualité environnementale considérée dans ce chapitre est un indice relatif à la perception que les agents ont de leur environnement local et est en lien avec la notion d'aménité. Aussi, ce développement

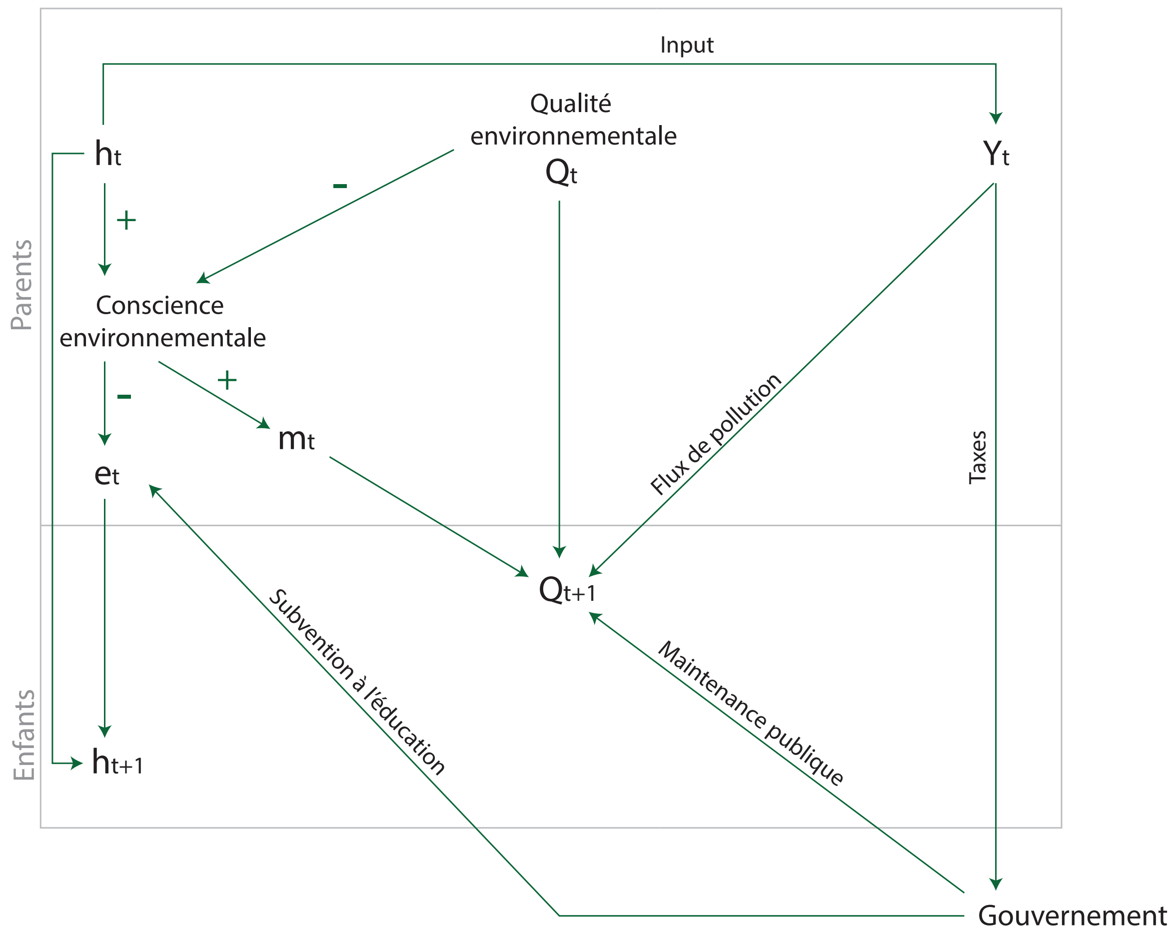


Figure 2: Schéma représentant la structure du modèle du chapitre 2.

durable local ne l'implique pas forcément à un niveau global. Nous obtenons également que cet équilibre peut se situer dans deux régimes, avec ou sans maintenance privée. Dit autrement, lorque l'État protège suffisamment l'environnement, les agents peuvent arrêter de contribuer à sa protection en dépît de l'intérêt qu'ils ont pour cela.

Par le biais d'une analyse dynamique, nous montrons également que la convergence vers cet équilibre de long terme peut se faire de manière oscillatoire, c'est à dire que des variations des niveaux de capital humain et de qualité environnementale vont être observées entre les générations. Cela implique, par exemple, que certaines générations font face à une bonne qualité environnementale au détriment de la suivante, c'est pourquoi nous nous y référons en tant qu'inégalités intergénérationnelles. Le mécanisme sous-jacent repose sur l'existence d'effets retours entre les préférences vertes et les niveaux de la qualité environnementale (Q) et du capital humain (h). Comme on peut le voir à l'aide du schéma 2, une augmentation de la conscience environnementale affecte l'arbitrage entre les choix privés des agents et implique, plus précisément, une augmentation des dépenses en maintenance (m) et une dimunution des dépenses d'éducation (e). La modification de ces choix va ensuite engendrer une hausse de la qualité environnementale et une baisse du capital humain des enfants. Cette génération aura donc des préférences vertes moins grandes, préférant s'occuper de problématiques plus économiques *etc.*

L'étude des effets de la politique à court et à long termes révèle qu'une augmentation de la taxe sur la pollution peut permettre à la fois d'éviter les inégalités intergénérationnelles et d'augmenter la croissance économique si le revenu de la taxe est bien alloué entre les deux postes de dépenses publiques. Plus précisément, s'agissant des effets de la politique sur les inégalités, il apparaît que la manière la plus simple de les éviter est que le gouvernement supporte seul la charge de la protection de l'environnement afin de lisser les comportements. En effet, dans ce cas, les ménages peuvent se focaliser sur leurs choix d'éducation, tandis que la protection de l'environnement est suffisante pour qu'ils cessent d'en faire de manière privée. S'agissant de la croissance, le scénario le plus favorable que nous avons identifié est obtenu également lorsque le gouvernement supporte suffisamment l'environnement pour être dans ce régime, mais le soutien à l'éducation doit également être suffisamment grand. Il est alors recommandé que les pouvoirs publics ne négligent pas un de ces deux postes (protection directe et éducation) pour favoriser le développement durable

De façon plus générale, nous mettons en exergue, dans ce chapitre, le rôle de la répartition du revenu de la taxe pour atteindre des objectifs environnementaux (*i.e.* améliorer l'environnement) et économiques (*i.e.* favoriser la croissance et diminuer les inégalités intergénérationnelles). De plus, si l'utilisation de politiques éducatives apparaît comme un outil intéressant pour sensibiliser les agents à l'environnement et les inciter à le protéger, le soutien public à la protection de l'environnement semble également requis.

0.4.3 Chapitre 3 : Politique environnementale et inégalités, une question de vie ou de mort

Dans ce dernier chapitre, nous cherchons à étudier les inégalités qui peuvent découler des effets de la pollution sur la santé et nous voulons évaluer le rôle que peut jouer une politique environnementale sur l'évolution des disparités entre les individus et sur le processus de croissance. Parmi les nombreuses mesures de santé, nous centrons ici notre attention sur la plus utilisée, à savoir l'espérance de vie (ou longévité).

Comme le révèlent de très nombreuses contributions empiriques, la pollution a des conséquences très importantes sur la santé, réparties inégalement au sein de la population. Des individus plus défavorisés, notamment en termes de capital humain, s'avèrent alors être plus sensibles aux effets négatifs de la pollution sur la santé. Parmi les explications mises en avant, il ressort que des individus moins éduqués ont tendance à vivre et à travailler dans de moins bonnes conditions et à bénéficier de moins d'informations sur les moyens de limiter ces effets. Malgré le nombre croissant de travaux empiriques sur cet aspect inégalitaire de la pollution et de travaux théoriques considérant les effets de la dégradation de l'environnement sur l'espérance de vie, aucune contribution n'a pour l'heure considéré la répartition inégale des effets de la pollution sur la longévité et ses conséquences économiques. L'objet de ce chapitre est alors de prendre en compte ce fait dans l'évaluation d'une politique environnementale.

Nous formalisons un modèle à générations imbriquées où un agent peut vivre jusqu'à trois périodes en fonction de sa longévité, qui dépend elle-même de la pollution et du niveau de capital humain de l'agent. Étant donné que nous voulons nous focaliser sur les effets de la pollution sur la santé, la pollution capture ici surtout la pollution de l'air qui est identifiée par l'OMS comme la source de pollution la plus meurtrière. La pollution est donc considérée sous la forme d'un flux, contrairement aux chapitres précédents.

Les individus ne diffèrent ici qu'en fonction du niveau du capital humain de leurs parents, qui influence ensuite leur propre niveau de capital humain, leur santé *etc.* Nous parlons alors d'inégalités pour faire référence aux disparités existantes au sein d'une même génération (inégalités intragénérationnelles).

Les agents se préoccupent de leurs propres niveaux de consommation mais aussi du niveau de capital humain de leurs enfants, à travers un altruisme paternaliste. Comme on peut le voir sur le schéma 3, l'accumulation du capital humain (h^i_{t+1}) est alors composée du temps d'étude choisi par les parents (e_t), de la transmission du capital humain du parent à l'enfant (h^i_t) et du capital humain moyen dans l'économie ($\bar{h}_t$), représentant le niveau du système éducatif. Alors que les deux premiers éléments représentent des forces divergentes, qui tendent à augmenter les disparités, le troisième élément est une force convergente, qui conduit au contraire à une réduction de ces disparités.

Une étude analytique et numérique du modèle nous permet d'identifier qu'il existe toujours un équilibre sans inégalité et une trappe à inégalités, où les disparités empirent au fil des générations. Cependant, la taille de cette trappe dépend du poids relatif des forces divergentes dans l'accumulation du capital humain. Simplement, lorsque ce poids est grand, la trappe à inégalités est très grande, de sorte que l'économie y sera piégée

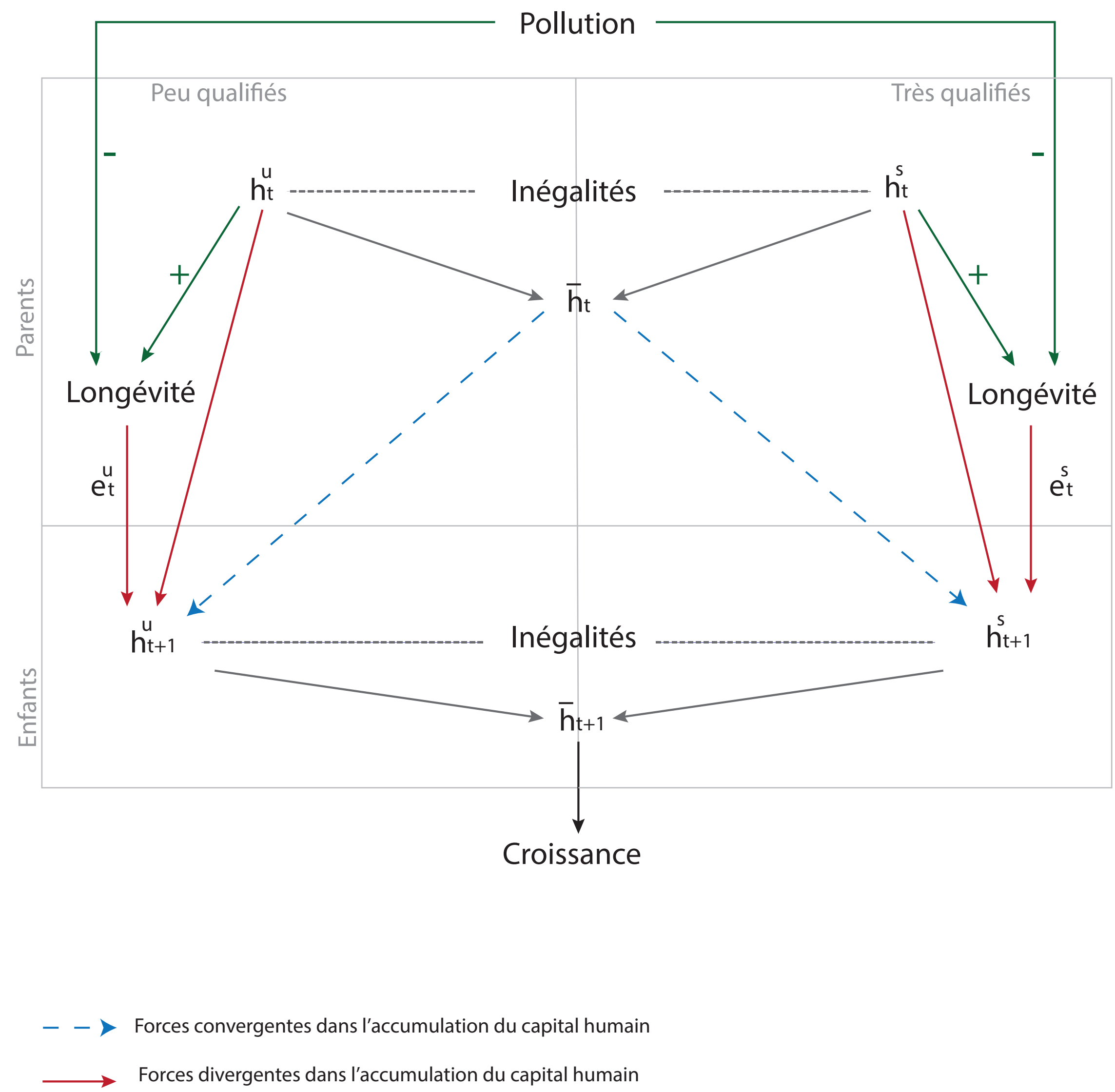


Figure 3: Schéma représentant la structure du modèle du chapitre 3.

pour la plupart de ses conditions initiales ; tandis que lorsque ce poids est faible, la trappe est de taille plus réduite et l'économie pourra converger vers l'équilibre de long terme sans inégalité beaucoup plus facilement. L'existence d'inégalités persistantes à long terme est ici due à la prise en compte de la longévité endogène et aux inégalités en santé qui en découlent. En effet, des disparités importantes en termes d'espérance de vie entraînent que les agents les plus défavorisés valorisent beaucoup moins le futur, ce qui implique que le rendement de leur investissement en éducation peut aussi être plus faible. Dans ce cas, les moins éduqués investissent moins en éducation, ce qui empire encore les disparités. La longévité occupant une place centrale dans la persistance des disparités à long terme, ses déterminants sont cruciaux pour identifier si une économie est dans la trappe ou non. En particulier, pour un niveau initial de pollution trop élevé, l'économie sera condamnée à un état où les agents les plus défavorisés le deviendront de plus en plus, tandis que si la pollution est suffisamment faible, l'économie peut converger à long terme vers un état sans inégalités.

En plus de leur coût pour les individus les plus défavorisés, nous trouvons que les inégalités sont également dommageables à la croissance de long-terme de l'ensemble de l'économie et apparaissent ainsi comme un frein au développement. Dans ce contexte, nous souhaitons étudier les implications d'une politique environnementale sur les inégalités et sur la croissance économique. Nous mettons en évidence qu'une augmentation d'une taxe sur la production polluante, associée à une maintenance environnementale publique, permet de réduire la taille de la trappe à inégalités, ce qui permet à l'économie d'y échapper. L'explication de ce phénomène tient au fait que la santé des individus les moins éduqués est plus sensible à la pollution. Par conséquent, une amélioration de la qualité environnementale permet d'augmenter davantage le rendement de l'éducation des enfants les plus défavorisés. Cependant, s'il existe toujours un niveau de taxe tel qu'une économie peut en sortir, celui-ci peut être déraisonable, car un niveau de taxe trop élevé nuit à la consommation et donc au bien-être de la population. Aussi, dans ce cas, des politiques supplémentaires visant à réduire les disparités en termes de capital humain devraient être implémentées en complément. Cependant, ces outils additionnels ne doivent pas se substituer à la politique environnementale, car le flux de pollution serait alors important, ce qui amplifierait les disparités existantes et diminuerait l'efficacité des instruments non-environnementaux. Enfin, nous montrons que la politique environnementale favorise la croissance de long-terme de l'économie, en raison de l'effet bénéfique de l'amélioration de l'environnement sur la santé et sur l'investissement en éducation de l'ensemble des agents.

Pour conclure, ce dernier chapitre nous a permis de montrer que des politiques environnementales pouvaient être utilisées également pour atteindre des objectifs économiques. En particulier, il met en évidence le rôle essentiel que peut jouer une politique environnementale dans la lutte contre les inégalités et dans l'amélioration des conditions économiques.

CHAPTER 1

Population Growth in Polluting Industrialization

1.1 Introduction

Pollution and its effects persist over time, even after the disappearance of the cause. Therefore, our present actions determine the well-being of future generations. From that, it seems crucial to look at individuals' behavior to understand long-term trends of pollution. Historically, the development of human activities has generated a huge increase in pollution, starting with the industrialization. This event represents a break in the effects of mankind on his environment and even the beginning of a new geological era: the *Anthropocene*. This term, coined by Crutzen & Stoermer (2000),[2] describes the current geological epoch where the impacts of human activities on earth and atmosphere are becoming predominant. Still informal, the large diffusion of this expression in the geological literature and its recognition by the Stratigraphic Commission of the Geological Society of London show the importance of the phenomenon and lead us to look into this period of development.[3]

The awareness of this phenomenon is confirmed by the extensive literature in environmental economics (see e.g. John *et al.* , 1995; Michel & Rotillon , 1995; Jouvet *et al.* ,

This paper is a joint work with Carine Nourry and Thomas Seegmuller. A slightly different version has been published in Resource and Energy Economics in 2014.

[2]Crutzen is the Nobel prize winning atmospheric chemist (1995) for discovering the effects of ozone-depleting compounds.

[3]See Zalasiewicz *et al.* (2008).

2000; Xepapadeas , 2005). Nevertheless, as emphasized by Brock & Taylor (2005), "the relationship between economic growth and the environment is and may always remain controversial". While some economists see the pollution-income relationship (PIR) as monotonically positive, others consider it as an inverted U-shaped curve, also known as the environmental Kuznets curve (EKC), discovered by Grossman & Krueger (1991) and so called by Panayotou (1995). According to the second group, the economic growth increases pollution in the early stages of development, but beyond some level of per capita income, the trend reverses, so that at high income levels, economic growth leads to an environmental improvement.

Here, we will introduce an important missing dimension inside this debate: the demographic one. Indeed, many papers highlight that population is a key element in the economic development process (see e.g. Ehrlich & Lui , 1997; Galor & Weil , 2000 or de la Croix and Licandro, 2013). Economists have rarely focused on the relationship between population, economic and pollution growth, as underlined by Robinson & Srinivasan (1997) and Chu & Yu (2002). We will study the effect of endogenous population growth *a la* Barro & Becker (1989) on factors accumulation during industrialization, focusing hence on the first part of the PIR where pollution and economic growth evolve in the same way.

Our motives for focusing on this complex link, at low development levels, stems from several intuitive elements. Concerning growth and population, a positive adjustment of the population size to an increase in per capita income was observed empirically during industrialization.[4] However, expansion of population has allowed a very important increase in production through a heavy increase in demand and in supply, favoring cumulative growth process (Bairoch , 1997). Regarding the connections between growth and pollution, we know that the production process often causes environmental damages. Nevertheless, as Dasgupta (2003) reminded, the environment is widely seen as a luxury

[4]This is shown in the study directed by Wrigley & Schofield (1981).

good: when a country is richer, environmental concerns are also stronger. With regard to population and pollution, on one hand, population growth generates *a priori* more pollution and resources depletion. But on the other hand, pollution, affecting well-being, influences reciprocally the demographic behaviors.

The aim of this paper is to develop a simple growth model with endogenous fertility and pollution change allowing to understand the evolution of capital intensity (a proxy of GDP per capita), population growth and pollution, during the process of industrialization.[5] In order to study the intergenerational aspects, we use an overlapping generations model. As in Jouvet *et al.* (2000), we consider a model with pollution, where a central role is given to altruism, but we adopt a paternalistic altruism: parents experience a warm glow from leaving bequest to their offspring, *i.e.* joy-of-giving.[6] As in Agee & Crocker (1998), we assume that parents' decisions for consumption have an impact on the environmental quality that they leave to their children. Nevertheless, instead of studying the interactions of this environmental bequest with the parent's investment in children's human capital, we analyze the interactions with a capital bequest which is better suited to the industrialization period (*i.e.* early stages of development). Environmental altruism is considered through the level of pollution that agents consider reasonable to leave to their children with respect to development, meaning that there exists a perception index of pollution adjusted to development. When households anticipate an increase in economic standard of living, they tolerate, as an acceptable compensation, a higher level of pollution for their children. This is, thus, not a standard green altruism but an index of future generations' well-being according to natural and economic environmental preoccupations. Note that it allows for the existence of a positive link between wealth and pollution, corresponding to what we observed in early

[5]There is a consensus in literature on the fact that there are two major events in development: industrialization and demographic transition. In this paper, we are only interested in the first process which represents early stages of development.

[6]This form of altruism is more suitable to study intergenerational externalities than dynastic altruism *a la* Barro (1974).

stages of development.

Concerning the characteristics of population in our framework, we adopt a cost of rearing children in terms of final good, appropriate for the early stages of development in which we are interested. Indeed, empirical evidences seem to highlight that the cost of raising children was quite stable and corresponded to a minimal cost ensuring subsistence.[7] It allows wealth and population to evolve in the same direction, as shown by empirical studies on this era. Moreover, we do not take into account explicitly mortality in our model, meaning that fertility and population growth are represented by the same variable, as in well-known contributions like Galor & Weil (2000). This assumption is supported by the stage under consideration where birth rate and population growth experience a common trend. In addition, historically, industrialization has corresponded to an increase in the birth rate, but not necessarily to a decrease in mortality.[8]

These key features of the model allow us to show that if the economy does not have too low initial conditions on wealth and population size, it experiences a polluting industrialization, *i.e.* the convergence to an equilibrium with high capital intensity, population growth but also high pollution. Indeed, the constant cost of rearing children in terms of final good favors a positive correlation between an increase in population size and a raise in capital intensity. Moreover, with environmental altruism, individuals accept a less healthy environment for their children if the economy is more developed, *i.e.* the population growth is larger. On the contrary, if the economy starts with too low initial conditions, it may be relegated to a poverty trap characterized by low levels of capital intensity, population growth and pollution. In this case, the wealth is not large enough to engage a growth process but the environmental quality is better. Finally, we demonstrate that a permanent technological shock, representing a major innovation,

[7]See *e.g.* Bairoch (1997). That is the reason why we choose a cost of rearing children in goods rather than a cost in time.

[8]See for example the case of France and the United States. In other countries, mortality decrease was weak. See Wrigley & Schofield (1981) and Galor (2005).

promotes a polluting industrialization process and is able to escape the economy from the poverty trap and to converge to the industrial steady state characterized by high levels of capital intensity, population growth and pollution.

In our model, the existence of steady states multiplicity and especially of the trap is determined by the interaction between demographic and environmental spheres. At odd with the literature, the existence of such a trap does not require market imperfection (see Murphy *et al.* , 1989; Matsuyama , 2004; Soares , 2005). Moreover, in our framework, endogenous demography is central to poverty trap, but not in the sense of the classic contribution of Nelson (1956), where high fertility is responsible for underdevelopment trap. Indeed, our trap results from a lack of fertility (as the children cost is too high) and from environmental perspectives (for too high persistence of pollution).

The paper is organized as follows. The next section presents the overlapping generations model with paternalistic altruism, endogenous fertility and pollution. Section 3 provides our explanation of polluting industrialization, analyzing steady states, dynamics and the effect of a permanent technological shock. We conclude in Section 4, while several technical details are relegated to an Appendix.

1.2 The Model

We present a simple overlapping generations model which allows us to analyze the trend of capital intensity, population growth and pollution during the early stages of the process of development, *i.e.* what we call a polluting industrialization. Our explanation is mainly based on the behavior of families, which make choices according to their two motives of altruism, a wealth one and an environmental one. Hence, to have a convenient model, the production sector and the pollution change are kept as simple as possible.

1.2.1 The Environment

Environment in early stages of development refers, as nowadays, to multiple concepts, but knowledge about it was limited and confined to local and observable elements. The perceived extent of pollution being limited, we focus on local environmental damages. However, its definition remains large, covering the following elements. In pre-industrial societies, pollution is mainly appreciated from an agrarian perspective through depletion of natural resource (*e.g.* deforestation) or insufficiency of agricultural production, linked with soil depletion, but also from an urban one referring especially to sanitary issues. With development toward industrial regime, other problems, closer to the present one, are added such as air and water pollution, due to the industrial production process. Keeping a large definition of the environment suitable for all the period studied, this index of local pollution can also represent a resource depletion index. Environmental quality will be described by an aggregate index, as usual in most of macro-dynamic models. We will use an index of pollution stock P_t which represents the environmental damages.[9] It evolves according to the following law of motion:

$$P_{t+1} = (1 - \alpha)P_t + aN_tc_t \tag{1.1}$$

with P_0 the pollution level in $t = 0$ which is given, N_t the population size and c_t the individual consumption, at period t.

The accumulation of pollution is due to aggregate consumption N_tc_t, with $a > 0$ the rate of pollution flow. The choice of a polluting consumption stems from the willingness to center our analysis on families' behavior. This usual assumption allows us to look at the effect of consumers on environment more directly than with polluting production[10]. The environment regenerates at a rate $\alpha \in (0, 1)$, *i.e.* in the absence of human activity, it

[9]Pollution stock is defined as the opposite of environmental quality. Hence, we will use the both terms interchangeably.

[10]The same choice was done by John & Pecchenino (1994), John *et al.* (1995), Ono (1996) *etc.*

can partly reconstitute itself. Such a phenomenon is called ecological resilience and refers to the reversible part of pollution. As we consider pollution as a stock that accumulates over time with emissions, we choose to exclude the case $\alpha = 1$, where pollution is a flow. This seems relevant since most pollutants remain in the ground, water or air for long periods and regeneration occurs at several speeds. To avoid free-riding problem, we do not formalize an environmental maintenance, as in John & Pecchenino (1994). Nevertheless, agents take into account the consequences of their consumption on local pollution and can reduce environmental degradation through their choices.

1.2.2 Family's behavior

We consider a representative family composed of two generations of agents: N adults and their children. The choices are made at family level, by a single head of family for the other members of his generation. The head is a representative agent who knows that the other family members follow his decisions. In order to examine the intergenerational consequences of family's choices, we develop an overlapping generations model with endogenous fertility and paternalistic altruism.[11]

We grant a fundamental place to altruism in our model, by studying two types of legacy: a wealth one, equivalent to a classic joy of giving (*i.e.* in term of capital bequest), and an environmental one, taking into account natural and economic environment. Each adult is interested in what he passes down to his children: a capital inheritance and a state of environment relatively to the development level (embodied by an environmental quality index). Thus, we will shed light on intergenerational transmissions of the capital and the environment and their interplays with other private decisions, concerning consumption and children, over agent's life-cycle.

Regarding environmental concerns, we assume that individuals take into account a

[11] The bequests are related to parental view on what is good for their heir, and to the pleasure they derive from giving. This paternalistic altruism allows a non optimal framework, essential to analyze externalities across generations.

perception index of environmental damages adjusted for population size. The choice of this particular form arises from two main considerations in line with the era studied. First, at early stages of development, as we emphasized above, households consider only local pollution. We formalize the perception of pollution, as suggested by Copeland & Taylor (1994), through an aggregate pollution adjusted for community size. Agents consider their contribution to the deterioration of environment and to depletion of natural resources, left to each of their children.[12] An other possible interpretation of the pollution per capita index can be find in Gutiérrez (2008) who uses it to represent a cost taken into account in the budget constraint. Her specification emphasizes the negative effect of pollution on health and appears as a cost shared upon society which indirectly affects amenity. Second, this index of pollution per capita allows us to consider a wealth-environment trade-off. In our framework, we study choices made at family level. Its size plays the role of family prosperity index (the coming family income) because larger the family, larger the workforce and larger the income. During early stages of development, production, either agricultural or industrial, used a large unskilled labor force (even children). Therefore, the size of a family seems to be a good index of its wealth. The head of family makes a trade-off between a lower level of pollution (lower resources depletion) and a higher level of family wealth. When they expect higher standards of living, they tolerate a higher level of pollution as an acceptable compensation.[13]

Agents live two periods, childhood and adulthood, but take all decisions during their second period of life. Adults are represented by the head of the family who makes the

[12] Note that defining pollution as the opposite of environmental quality in our model, this negative amenity in terms of resources depletion per capita, can also be considered as a positive amenity in terms of resources per capita bequeathed to the children. See Marini & Scaramozzino (1995) for a similar amenity for resources per worker.

[13] As illustrations of this compromise, Bairoch (1997) observes that migration toward city associated with the industrialization process of England, was accompanied by urban excess of death and appalling life conditions. Williamson (1985) and Brown (1990) found also that a large part of the raise in wage in factories, during industrialization, appears to be explained as a compensation for poor working and living conditions. At the aggregate level, before and during industrialization process, population size was a good proxy for economic growth and development (see e.g. Maddison , 2001; Galor , 2005).

choices for them. The leader takes into account individual preferences of each relative of his generation. An agent, born in $t-1$, cares about his consumption level during his second period of life (c_t), his number of children (n_t), the amount of capital kept at life-ending with the intention to bequeath it to his children ($x_t \equiv n_t k_{t+1}$). Finally, he values negatively the levels of perceived pollution that he suffers when adult ($\Pi_t \equiv P_t/N_t$) and that he leaves to the future generation ($\Pi_{t+1} \equiv P_{t+1}/N_{t+1}$). Note that the negative amenity due to perceived pollution bequeathed to children is weighted by population growth. It acts as an altruism factor: the more children agent wants, the more he is affected by the pollution he leaves to them.

We choose to represent preferences through a specified utility function to have a simple model, which captures, however, the mechanisms we want to emphasize. The preferences of an individual born in $t-1$ are defined by the following utility function of the head of the family:

$$\ln c_t + \epsilon_1 \ln x_t - \epsilon_2 n_t \frac{\Pi_{t+1}^{1+\mu_3}}{1+\mu_3} - \epsilon_3 \frac{\Pi_t^{1+\mu_3}}{1+\mu_3} \tag{1.2}$$

where $\epsilon_1 > 0$ and $\epsilon_2 > 0$ are the paternalistic altruism factors on wealth and environmental concerns, respectively, and $\mu_3 > 0$.

During their first period of life, agents are children and economically inactive, but they generate an individual cost of rearing, $\beta > 0$, to their parents. We assume a constant cost in terms of final good, which allows wealth and population to evolve in the same direction. Such an assumption is appropriate for the pre-industrial period, and is justified empirically in this era where the cost of raising a child seems to remain stable and weak. Indeed, before and during the beginning of the industrialization process, it corresponds to a simple cost necessary to ensure children's subsistence, notably weakened by child labor and the lack of education.[14]

[14] Child labor did not stop with industrialization but intensified (Horrell & Humphries , 1995). Concerning education, although the industrial revolution is a technical revolution, it especially required a

During their second period of life, each agent supplies inelastically one unit of labor remunerated at the wage rate w_t and inherits an amount of capital k_t from his parents remunerated at the return R_t. These incomes are shared between consumption c_t, bequest x_t, and children rearing βn_t. Thus, an adult faces the following budget constraint:

$$c_t + n_t(k_{t+1} + \beta) = R_t k_t + w_t \tag{1.3}$$

Finally, the number of adults in period t N_t is given by the number of adults in $t-1$ N_{t-1} multiplied by the number of children they choose to have at this period n_{t-1}. Therefore, the evolution of population is given by:

$$N_t = n_{t-1} N_{t-1} \tag{1.4}$$

with $N_0 = 1$ given.

Maximizing the utility function (1.2) subject to the budget constraint (1.3), the pollution change (1.1) and the changes in population (1.4) corresponds to the following program:

$$\max_{n_t, k_{t+1}} \quad \ln\left(R_t k_t + w_t - n_t(k_{t+1} + \beta)\right) + \epsilon_1 \ln\left(n_t k_{t+1}\right) \\ -\epsilon_2 \tfrac{n_t}{1+\mu_3} \left(\tfrac{(1-\alpha)P_t + aN_t(R_t k_t + w_t - n_t(k_{t+1}+\beta))}{N_t n_t}\right)^{1+\mu_3} - \tfrac{\epsilon_3}{1+\mu_3} \left(\tfrac{P_t}{N_t}\right)^{1+\mu_3}$$

It leads to two first order conditions. The first one corresponds to the agent's trade-off in term of capital and is given by:

$$c_t^{-1} = \epsilon_1 x_t^{-1} + \epsilon_2 \; a \; \Pi_{t+1}^{\mu_3} \tag{1.5}$$

large numbers of low-skilled workers in its first stages and was not accompanied by major progresses in education (Thompson , 1963; Bairoch , 1997).

Reducing consumption to increase capital bequest has a cost corresponding to the marginal utility (c_t^{-1}) and a direct benefit through the marginal utility (x_t^{-1}) weighted by the altruism factor ϵ_1. However, a second benefit goes through environmental quality: consumption being polluting, increasing bequest generates a marginal gain through the decrease of pollution. Hence, individuals make their choices between consumption and bequest according to the amenity provided directly by these two elements, but also according to the welfare associated to environmental altruism.

The second trade-off summarizes the choice in term of children:

$$(k_{t+1} + \beta)\ \left(c_t^{-1} - \epsilon_2\ a\ \Pi_{t+1}^{\mu_3}\right) = \epsilon_1\ n_t^{-1} + \epsilon_2 \left[\Pi_{t+1}^{1+\mu_3} - \frac{\Pi_{t+1}^{1+\mu_3}}{1+\mu_3}\right] \tag{1.6}$$

To understand this choice, we have to interpret again the marginal costs and benefits of having children. Concerning the costs of having more children, there is the renouncement to consumption ($(k_{t+1} + \beta)c_t^{-1}$) due to the increase in bequest and rearing cost. This effect is, nevertheless, mitigated by the fact that a lower consumption corresponds also to a benefit in terms of environmental quality because households pollute less ($\epsilon_2\ a\ \Pi_{t+1}^{\mu_3}(k_{t+1} + \beta)$). Concerning the marginal benefits, an adult enjoys having children, through his altruism in terms of wealth ($\epsilon_1\ \frac{1}{n_t}$). A second marginal benefit derives from the relative environmental altruism. For a given pollution stock, an increase in the fertility rate corresponds to a lower pollution stock per capita, which is the index perceived by agents ($\epsilon_2 \Pi_{t+1}^{1+\mu_3}$). This effect is, however, reduced by the increasing weight associated with the pollution index: when adults have more children, they are more affected by pollution because they want a healthy environment for them ($\epsilon_2 \frac{\Pi_{t+1}^{1+\mu_3}}{1+\mu_3}$).

Using the first trade-off (1.5), equation (1.6) rewrites:

$$\Pi_{t+1} = \left[\beta \frac{\epsilon_1}{\epsilon_2}\ \frac{1+\mu_3}{\mu_3} x_t^{-1}\right]^{\frac{1}{1+\mu_3}} \equiv\ g(x_t) \tag{1.7}$$

Remark 1 *g is a decreasing function, meaning that there is a negative relationship between the pollution index Π_{t+1} and the capital bequest x_t and thus a positive one between bequest in wealth and bequest in perceived environmental quality.*

Substituting (1.7) into (1.5), we obtain:

$$c_t = \left[\epsilon_1 \, x_t^{-1} + \epsilon_2 \, a \, \left[\beta \frac{\epsilon_1}{\epsilon_2} \frac{1+\mu_3}{\mu_3} x_t^{-1} \right]^{\frac{\mu_3}{1+\mu_3}} \right]^{-1} \equiv \; h(x_t) \tag{1.8}$$

Remark 2 *h is an increasing function, revealing the positive relationship between consumption c_t and bequest x_t.*

Hence, the optimal behavior of agents can be summarized by two equations, which determine the connections between individual consumption c_t, wealth's bequest x_t and pollution index Π_{t+1}. It is important to notice that both forms of altruism are needed for our analysis. Indeed, without wealth's altruism, there is no capital, *i.e.* no production. Without environmental altruism, the net benefit of having children is lower than the one of investing an additional unit in capital. In this case, the economy degenerates again.

1.2.3 Firms

Since our model focus on consumer's behavior, production sector is quite obvious. A unique final good is produced by a representative firm. The production is given by $Y_t = AK_t^s N_t^{1-s}$, where K_t is aggregate capital, N_t aggregate labor, $A > 0$ the total productivity of factors and $s \in (0,1)$ the capital share in total income. The economy is perfectly competitive. From profit maximization, we get:

$$R_t = sAk_t^{s-1} \quad \text{and} \quad w_t = A(1-s)k_t^s \tag{1.9}$$

where R_t denotes the real return to capital, w_t the real wage and $k_t \equiv K_t/N_t$ the capital intensity. Note that, to simplify results, we assume a full depreciation of capital. Within a two periods overlapping generation model, it is justified by the length of a period.

1.2.4 Intertemporal equilibrium

Substituting (1.9) in the budget constraint (1.3), we get the resource constraint:

$$c_t + x_t + \beta n_t = A\, k_t^s \tag{1.10}$$

Using $\Pi_{t+1} = P_{t+1}/N_{t+1}$ and as $N_{t+1} = n_t N_t$, we can rewrite the evolution of pollution (1.1) as:

$$n_t \Pi_{t+1} = (1-\alpha)\Pi_t + a c_t \tag{1.11}$$

Finally, using functions g and h, we obtain the following definition:

Definition 1 *Given the initial conditions* $k_0 \geqslant 0$ *and* $\Pi_0 = \frac{P_0}{N_0} \geqslant 0$*, an intertemporal equilibrium is a sequence* $\{x_{t-1}, k_t\}$*, for all* $t \geqslant 0$*, such that the following dynamic system is satisfied:*

$$\left\{ \begin{array}{rcl} h(x_t) + x_t + \beta \frac{x_t}{k_{t+1}} & = & A\, k_t^s \\ \frac{x_t}{k_{t+1}}\, g(x_t) - a\, h(x_t) & = & (1-\alpha)\, g(x_{t-1}) \end{array} \right. \tag{1.12}$$

We notice that, at period t, the two variables $x_{t-1} = n_{t-1}k_t$ and k_t are predetermined.[15]

1.3 An explanation of polluting industrialization

Using this framework, we will be able to exhibit what we call a polluting industrialization. We start with some preliminary results related to the existence of steady states. Then, analyzing dynamics, we show that there exist sets of initial conditions such that

[15] x_{t-1} is predetermined because $x_{t-1} = g^{-1}(\Pi_t)$ and Π_t is predetermined.

the economy experiences a polluting industrialization, *i.e.* an increase in capital intensity, population growth and pollution. Finally, we will look at the effect of a permanent technological shock in the case where the economy is stuck on a pre-industrial trap with low levels of capital intensity, population growth and pollution.

1.3.1 Preliminary results: steady states analysis

As a preliminary study of dynamics, the steady state analysis will allow us to understand some long-term trends of the economy. We will show the existence of two steady states. The first one is characterized by relatively low levels of capital intensity, population growth and pollution and will determine a poverty trap. The second one will represent the outcome of a process of industrialization with larger capital intensity, population growth and pollution.

From Definition 1, it follows that:

Definition 2 *A steady state equilibrium of the dynamic system (1.12) is defined as a solution, (x, k) satisfying:*

$$\begin{cases} k = \left[\frac{1}{A}\left[\beta(1-\alpha) + x + \left(1 + \frac{\beta a}{g(x)}\right) h(x)\right]\right]^{\frac{1}{s}} \equiv \Psi_1(x) \\ \\ k = \frac{x}{(1-\alpha)+a\; h(x)\; g(x)^{-1}} \equiv \Psi_2(x) \end{cases} \tag{1.13}$$

In order to characterize the solutions of (1.13), we begin by exhibiting some properties of $\Psi_1(x)$ and $\Psi_2(x)$:

Lemma 1

1. Ψ_1 is a strictly increasing function, where $\Psi_1(0)$ is strictly positive and $\lim_{x\to+\infty} \Psi_1(x) = +\infty$.

2. There exists a value x^* such that $\Psi_2(x)$ is increasing for all $x \leqslant x^*$ and decreasing for all $x \geqslant x^*$. Furthermore, $\Psi_2(0) = 0$ and $lim_{x\to+\infty}\Psi_2(x) = \beta\;\epsilon_1\;(1+\mu_3)/\mu_3 > 0$.

Proof. See Appendix 1. ■

This lemma allows us to show the coexistence of two steady states as it is illustrated in Figure 1.1 and shown in the following proposition.

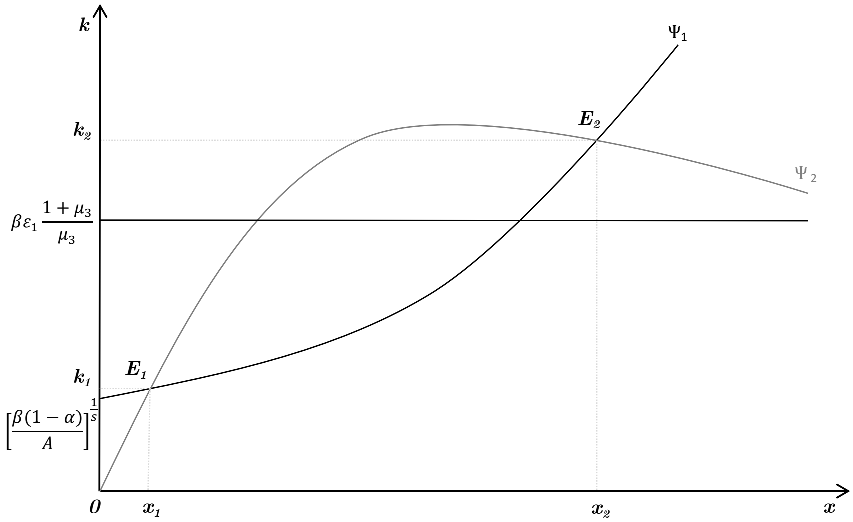


Figure 1.1: Representation of $\Psi_1(x)$ and $\Psi_2(x)$ and existence of two steady states

Proposition 1 *For β sufficiently weak, there exist two steady-state equilibria: a pre-industrial one (x_1, k_1) and an industrial one (x_2, k_2). The latter equilibrium is characterized by a larger:*

- *capital intensity ($k_2 > k_1$)*
- *bequest ($x_2 > x_1$)*
- *individual consumption ($c_2 > c_1$)*
- *population growth ($n_2 > n_1$)*
- *pollution stock ($P_2 > P_1$)*

The industrial steady state corresponds also to a lower pollution per capita ($\Pi_2 < \Pi_1$).

Proof. See Appendix 2. ■

The industrial steady state is characterized by larger levels of capital intensity, individual consumption, fertility growth[16] and pollution stock. Hence, it perfectly corresponds to the long-term state of a regime initiated by industrialization and pointing up a high capital intensity, and therefore, GDP per capita, but also a large population growth and a deterioration of environment quality. Our model allows to represent the first part of the environmental Kuznets curve.

From a theoretical perspective, two key mechanisms lead to the industrial equilibrium. First, the constant rearing cost in term of goods implies that a higher fertility rate is compatible with a higher wage, and therefore with a higher capital intensity. Second, the environmental altruism tolerates a higher pollution if development goes up too. This explains that a higher capital intensity and population growth are in accordance with a higher pollution, as observed historically.

As we can see in Figure 1.1, the interactions between demographic and environmental spheres are crucial for our results. The existence of the low equilibrium E_1 is provided by the vertical intercept of Ψ_1, which depends on the proportion of remaining pollution from one period to the next $(1-\alpha)$ and the cost of raising children (β). Besides, we note that with the environment as a flow $(\alpha = 1)$, the multiplicity of steady states does no longer exist.[17]

In our model, population driving development, economies with higher population growth are characterized by higher capital intensity, on the contrary to standard results of OLG models with pollution, as in Gutiérrez (2008). But in accordance with her, it corresponds nevertheless to a lower level of pollution per worker. Indeed, as shown in Proposition 1, despite the higher level of pollution at the industrial equilibrium, the per capita index taken into account by agents is lower, due to the larger increase in

[16]We can see in Appendix 2 that $n > 1$ for A sufficiently high, at least at the industrial steady state.
[17]However as explained in Section 2.1., we choose to exclude this limit case.

population.

To understand the consequences on welfare, utility function evaluated at a steady state can be written:

$$\ln h(x) + \epsilon_1 \ln x - \frac{\epsilon_2 n + \epsilon_3}{1 + \mu_3} \; g(x)^{1+\mu_3} \tag{1.14}$$

where $g(x)$ and $h(x)$ are defined in (1.7) and (1.8) respectively. At the higher steady state, consumption is larger, as well as capital bequest. Concerning disutility for pollution, two opposite effects remain. The per capita index of pollution diminishes, which corresponds to a positive amenity on aggregate utility function. But the increase in number of children exacerbates this disutility for pollution. From the definition of $g(x)$, we can demonstrate that for μ_3 sufficiently weak, the first effect dominates.[18] The industrial equilibrium is thus Pareto superior to that without industrialization.

1.3.2 Transitional dynamics

In this section, we enrich the study of steady states multiplicity with the analysis of their dynamics. This allows us to bring out divergences in economies' development, as observed historically with distant dates of priming transition. Indeed, whereas the process of industrialization started in England in the early eighteenth century, it has spread gradually and slowly to other countries (in France, it began 50 years after England; in Germany, Canada and United-States, 100 years after; in Japan and Russia, 120 years after), not to mention most of developing countries where it happened only recently (around the middle of the 20th century).[19] Over the course of history, we have thus observed simultaneously economies in both regimes, the pre-industrial one and the industrial one. We will see that our model allows to explain these features, establishing in addition a link with pollution emissions.

[18]Proof available upon request.
[19]See Bairoch (1997).

The study of dynamics is carried out in a phase diagram. Considering the dynamic system (1.12), we are able to evaluate the two loci of points such that $\Delta x_{t-1} = 0$ and $\Delta k_t = 0$, which devide the space into several regions. We can then plot the dynamics in these different regions: as depicted in Figure 1.2, x_{t-1} decreases (increases) below (above) the locus where $\Delta x_{t-1} = 0$, while k_t increases (decreases) below (above) the locus where $\Delta k_t = 0$. Therefore, the industrial steady state E_2 is stable, whereas the pre-industrial one E_1 corresponds to an unstable saddle point, leading to a poverty trap.

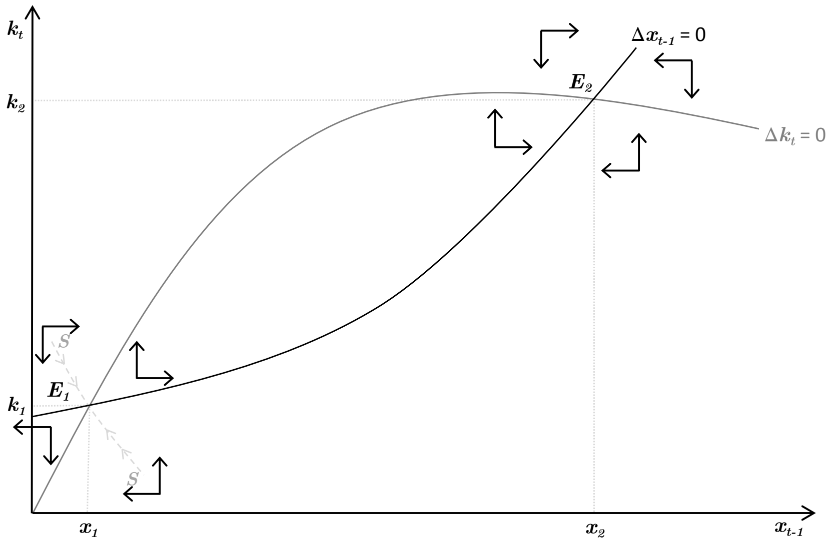


Figure 1.2: Transitional dynamics

These results are summarized in the following proposition.

Proposition 2 *For β sufficiently weak, the industrial steady state E_2 is stable and the pre-industrial one E_1 is an unstable saddle point with a stable manifold SS. Below SS, the economy is stuck on a poverty trap, whereas above SS, the economy converges to the industrial steady state.*

Proof. See Appendix 3. ■

For initial conditions such that the economy starts above the border SS, wealth is high enough to generate an income effect which allows a more substantial bequest, a larger individual consumption and a higher fertility. It also leads to a lower pollution per capita, implying that the increase in expected family size is more important than that of pollution. Therefore, the economy develops and converges, in the long run, to the industrial steady state E_2. The convergence to the industrial equilibrium, rather than infinite progress, is due to some restoring forces. First, the rearing cost of children β, which is a cost per child, is constant so that the total cost of children does not stop to grow with the number of children. Second, since adults have a distaste effect for consumption through pollution, they make a trade-off between these two variables and prefer to decrease their consumption when pollution becomes too large. Finally, decreasing returns on capital limits directly the income effect and hence the increase in wealth.

When the initial conditions are located below the SS curve, the economy is relegated to a poverty trap, defined by Azariadis & Stachurski (2005) as “any self-renforcing mechanism which causes poverty to persist". If the initial level of capital is too low, the agent’s income is too low with respect to the cost of raising children. Families cannot grow to earn more income. They do not have the resources to have children and to bequeath. They fail to develop, keeping the economy in the poverty trap. In this case, the economy can never reach the higher steady state (E_2) and is characterized by a low capital intensity, a low population growth and a low pollution level.

Our dynamics is similar to that obtained by Bulte & Horan (2003). It leads to two steady states: a stable one which is more economically desirable, and a saddle point corresponding to the bad scenario. However, studying different issues, our results according to environmental perspective are different. While quoted authors focus on wildlife habitat conservation and agricultural expansion choices, we are interested in the industrialization process. In our model, the stable equilibrium, offering higher income, does not refer to a positive scenario in terms of nature but presents a higher level of pollution stock. However, the lower level of pollution per capita at the higher steady state implies that it may still be more desirable for agents. Indeed, in opposition to a large part of literature on poverty trap with environment, this vicious circle of poverty does not correspond also to a pollution trap, *i.e.* with a persistent low environmental quality (see e.g. John & Pecchenino , 1994; Ikefuji & Horii , 2007; Mariani *et al.* , 2010). The main reason for this outcome is that we do not consider the same level of development. We focus on the beginning of development process, *i.e.* industrialization, while the previous papers look at more advanced stages of development, after the demographic transition process.[20] At the lower steady state, industrialization has not happened yet. Environmental quality at E_1 is thus higher than at the industrial steady state E_2. This result is in line with the observations of climatologists (e.g. Crutzen & Stoermer , 2000) but also with the one of historians who underline the bad quality of life during the industrial revolution (e.g. Bairoch , 1997).

As shown in Section 3.1, the interaction of environmental and demographic spheres are at the origin of the existence of multiple equilibria and consequently of the poverty trap. More precisely, an increase in parameters diminishing fertility (cost of children) and/or an increase in pollution (persistence rate of pollution) will raise the size of the trap. In contrast with much of the development literature, the existence of the poverty trap does not require any market imperfections (see for example well-known contributions of Murphy *et al.* , 1989; Matsuyama , 2004). Moreover, despite the central nature of fertility in our framework, the underdevelopment trap does not correspond to a demographic trap in the sense of Nelson (1956), where population growth is high. Instead and in accordance with the development stages studied, our trap corresponds to low fertility levels, which do not allow enough family wealth.

Being interested in the development process and in the role of population inside it,

[20]Literature on long term development identifies two major events in development process, the industrialization (led by technological progress) and the demographic transition (due to education). See Galor (2005).

we emphasize two different scenarios depending on initial conditions. At a given weak level of capital intensity k, the economy can experience two different configurations of dynamics.

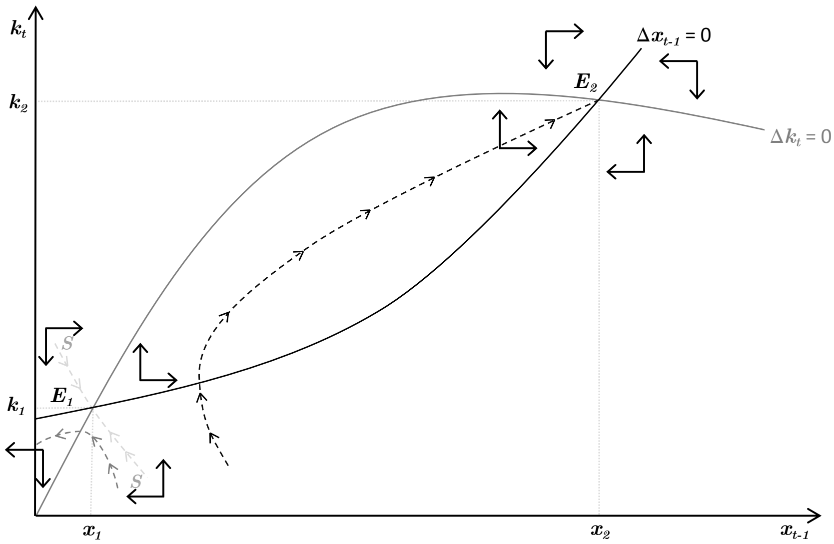


Figure 1.3: Two scenarios of developing countries dynamics

When n is high enough, *i.e.* above the poverty trap (dashed black manifold), the economy takes off. First, the population growth decreases because the rearing cost β is too high relatively to wealth. It has a direct effect on capital per capita k which increases mechanically. Then, the capital level is sufficient to generate an income effect allowing to achieve higher levels of consumption, capital intensity and population growth. These increases generate also a deterioration of the environment, corresponding to the first part of the environmental Kuznets curve where pollution worsens as country's income grows. Nevertheless, the index of environment improves, *i.e.* the rise in the economic environment (family size as index of wealth) is higher than the deterioration of natural environment (pollution).

In the second scenario (dashed grey manifold), n is too low, and economy is actually stuck in the poverty trap. The first step is identical, population growth decreases, which induces an increase in capital per capita. But k does not increase sufficiently and so fails to ensure the subsistence of a larger population. In longer run, the lack of population introduces a lack of workforce and makes the economy poorer. Conditions are not sufficient to generate the economy take-off. However, the low levels of consumption and population bring on a weak pollution level, but also a relatively bad index of environment because of the lack of economic development.

These scenarios highlight the role of agent's behaviors and especially of population in the process of industrialization. Through this simple model, we are able to provide an explanation for the start of the development process. These results contrast with conventional wisdom on population and development, (supported by Malthus , 1798), which considers fertility as a possible cause of underdevelopment. On the contrary, we underline the role it can play in industrialization process, affecting positively demand and labor force. Even if mechanisms are different, we are in line with the optimistic approaches of Boserup (1965) or Simon (1981), who argue that larger population exerts pressure for innovation and allows for scale economies.[21] An increase in population growth appears to be a possible stimulus for the development of economy in this time, in accordance with economic historians as Habakkuk (1971). From a demographic perspective, our results are in accordance with the well-known paper of Galor & Weil (2000) in early stages of development, where technological progress is a function of overall population size. However, in our paper, the mechanism associated with industrialization is provided not only by population, but by its interaction with environment in consumers' preferences. Furthermore, we note that our framework is close to that of unified growth theory, as in Galor & Weil (2000) or in Galor & Moav (2002). However, their analyzes focus more on the role of human capital in the development process, and espcecially in

[21] A more recent contribution, Jones (1999), shows the positive effect of population on per capita income through innovation but without scale effects.

the demographic transition leading to modern economic growth.

Note that dynamics generates an endogenous polarization of the world economies, with the coexistence of a poverty trap and an industrial stable steady state. It illustrates the heterogeneous experiences of countries during the convergence process, and explains that at the same time some countries were already engaged in the industrial process while others were still stuck in the pre-industrial trap. Achieving a long-run equilibrium rather than the other is historically dependent: history determines the initial conditions inherited by the economy, and ultimately defines the equilibrium toward which it tends (as e.g. Mookherjee & Ray , 2003). Therefore, as emphasized by Azariadis & Stachurski (2005), disparities would persist without a suitable shock or policy intervention. This is the object discussed in Section 3.3.

1.3.3 Impact of a technological shock

The question we address now is the following: could a major technological innovation reverse the dynamics of an economy located in the trap, allowing it to converge to the stable industrial steady state? As we have already specified, we consider a simple production sector. Therefore, a permanent technological change is interpreted as a permanent and positive shock on the productivity of factors A. As illustrated in Figure 1.4, when A increases, the curve $\Delta x_{t-1} = 0$ shifts down (becoming the dashed curve $\Delta x'_{t-1} = 0$) and the stable manifold SS is pushed down toward $(0, 0)$. It leads to two new steady states E_1' and E_2'. The increase in productivity facilitates the beginning of the mechanism of growth and convergence towards the industrial steady state, by increasing instantaneously the output, and therefore, by encouraging the development process described previously.

We can summarize the results about the effects of a positive permanent technological shock in the following proposition.

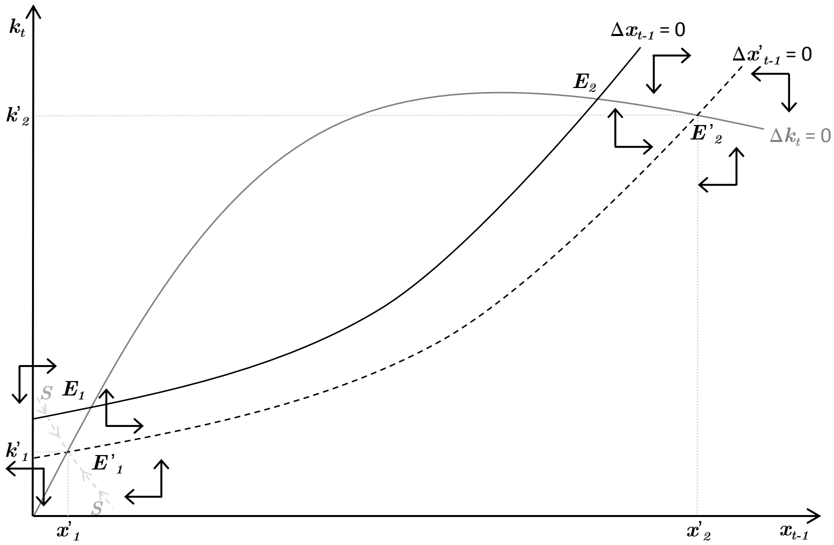


Figure 1.4: Impact of a positive technological shock

Proposition 3 *For β sufficiently weak, a permanent and positive shock reduces the pre-industrial trap, so that:*

- *an economy in the low-development trap but sufficiently close to* E_1*, will converge to the industrial steady state;*
- *an economy in the poverty trap may always tend to the industrial steady state if the technological shock is large enough.*

As described in Figure 1.4, following the technological shock, the *old* unstable steady state E_1 enters the region where one converges to the *new* industrial steady state E_2'. Thus, a sufficient technological innovation favors the transition to the industrial long-term equilibrium and always allows the economy to escape from the low-development trap. Note that such a shock only conducts the economy to a new dynamic path where it converges in the long run, to an equilibrium with higher levels of capital intensity, population growth and pollution. This process is hence continuous and progressive, in accordance with the empirical evidence and with the fact that historians prefer the term “industrialization process" to “industrial revolution".

In this model, technological innovations are exogenous, accordingly we give some insights on their possible origins and on their implications. Such technological improvement may represent a major innovation coming directly from inside of the economy (as the steam engine), but also from the diffusion of technology from abroad. Historically, the diffusion of technological innovations apparently played a key role in the takeoff of other countries than England, where industrialization started. Indeed, it had spread first to geographically close countries (western europe) and then to economically and politically related countries (united-states, canada). In this sense, McCord & Sachs (2013) highlight for example that the closer a country is to England, the earlier the date of reaching the threshold of $ 2,000 per capita.

Therefore, our results support the role of technological transfer policies in helping the least developed countries to escape the trap permanently. In this way, our paper is in line with the literature on the “big push", which emphasizes the importance of development policy (investment and aid) to break out of the poverty trap and to start the industrialization process (e.g. Rosenstein-Rodon , 1943; Murphy *et al.* , 1989; Soares , 2005). Here, more precisely, some economies require only a “little pull" *a la* Bulte & Horan (2003) to move towards an industrialized equilibrium, while others, characterized by a lower initial levels of capital and population, will need further innovations to engage the process of industrialization.

Thus, this simple framework allows to reproduce the first stages of the economic development, the associated environmental damages and the role of a permanent technological shock in the priming of this mechanism.

1.4 Conclusion

In this paper, we develop a simple overlapping generations model, to explain the process of industrialization, characterized not only by an increase in capital intensity and population growth, but also by a rise of pollution. We bring out the role of finite-lived agents in this process through their altruism and their family choices. A key feature of our explanation is the introduction of an environmental altruism, which stipulates that adults agree to leave a lower quality of natural environment to their children, if they expect an improvement of the economic environment. A second important feature of our framework is the introduction of a constant rearing cost per child in terms of the final good, which seems to be a realistic assumption when one focuses on the period of industrial revolution.

We show that the economy may converge to an industrial steady state with high levels of capital intensity, population growth and pollution. However, when the initial conditions on wealth and population size are too low, the economy is relegated to a poverty trap. Finally, a permanent technological shock that we associate to a major innovation promotes the convergence to the industrial steady state.

1.5 Appendix

1.5.1 Appendix 1: Proof of Lemma 1

Substituting $g(x)$ and $h(x)$, given by (1.7) and (1.8) respectively, in the system (1.13), we get:

$$\begin{cases} \Psi_1(x) & = & \left[\frac{1}{A}\left(\beta(1-\alpha)+x\left[1+\frac{1+\beta a \gamma^{\frac{-1}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}{\epsilon_1+\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}\right]\right)\right]^{\frac{1}{s}} \\ \\ \Psi_2(x) & = & \frac{x\gamma^{\frac{1}{1+\mu_3}}}{(1-\alpha)\gamma^{\frac{1}{1+\mu_3}}+a\ \frac{x^{\frac{2+\mu_3}{1+\mu_3}}}{\epsilon_1\ +\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}} \end{cases}$$

with $\gamma \equiv \beta\frac{\epsilon_1}{\epsilon_2}\ \frac{1+\mu_3}{\mu_3}$.

Study of the function Ψ_1

We have $\Psi_1(0) = \left[\frac{\beta(1-\alpha)}{A}\right]^{\frac{1}{s}} > 0$ and $\lim_{x\to+\infty}\Psi_1(x) = +\infty$. Computing the first order derivative of $\Psi_1(x)$, we obtain:

$$\Psi_1'(x) = \frac{1}{s}\frac{1}{A}\frac{x^{\frac{1}{1+\mu_3}}\left[2\epsilon_1\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}}+\frac{\mu_3}{1+\mu_3}\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}}+\frac{2+\mu_3}{1+\mu_3}\ a\ \gamma^{\frac{-1}{1+\mu_3}}\beta\ \epsilon_1\right]+x^{\frac{2}{1+\mu_3}}\left[\epsilon_2^2\ a^2\ \gamma^{\frac{2\mu_3}{1+\mu_3}}+\beta a^2\epsilon_2\gamma^{\frac{-1+\mu_3}{1+\mu_3}}\right]+\epsilon_1(1+\epsilon_1)}{\left(\epsilon_1+\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}\right)^2}$$
$$\left[\frac{1}{A}\left(\beta(1-\alpha)+x\left[1+\frac{1+\beta a\gamma^{\frac{-1}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}{\epsilon_1+\epsilon_2\ a\ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}\right]\right)\right]^{\frac{1-s}{s}} > 0$$

meaning that $\Psi_1(x)$ is a strictly increasing function, with $\Psi_1'(0) = \frac{1}{s}\frac{1}{A}\left(1+\frac{1}{\epsilon_1}\right)\left[\frac{1}{A}\beta(1-\alpha)\right]^{\frac{1-s}{s}}$

Study of the function Ψ_2

We have $\Psi_2(0) = 0$ and $\lim_{x\to+\infty}\Psi_2(x) = \epsilon_2\ \gamma$. Using

$$\Psi_2(x) = \frac{x\gamma^{\frac{1}{1+\mu_3}}}{(1-\alpha)\gamma^{\frac{1}{1+\mu_3}} + a\, H(x)} \ , \quad \text{with } \ H(x) \equiv \frac{x^{\frac{2+\mu_3}{1+\mu_3}}}{\epsilon_1 \ + \epsilon_2 \ a \ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}}$$

the first order derivative of $\Psi_2(x)$ is given by:

$$\Psi_2'(x) = \frac{\gamma^{\frac{1}{1+\mu_3}} \left[(1-\alpha)\gamma^{\frac{1}{1+\mu_3}} + aH(x)\right] - x\gamma^{\frac{1}{1+\mu_3}} aH'(x)}{\left[(1-\alpha)\gamma^{\frac{1}{1+\mu_3}} + aH(x)\right]^2}$$

with $H'(x) = \frac{\epsilon_1 \ \frac{2+\mu_3}{1+\mu_3} x^{\frac{1}{1+\mu_3}} + x^{\frac{2}{1+\mu_3}} \epsilon_2 \ a \ \gamma^{\frac{\mu_3}{1+\mu_3}}}{\left[\epsilon_1 \ + \epsilon_2 \ a \ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}\right]^2} > 0.$

Therefore,

$$\Psi_2'(x) \geqslant 0 \Leftrightarrow \gamma^{\frac{1}{1+\mu_3}} (1-\alpha) \geqslant J(x) \ , \quad \text{with} \quad J(x) \equiv \frac{a\epsilon_1 \ x^{\frac{2+\mu_3}{1+\mu_3}} \frac{1}{1+\mu_3}}{\left[\epsilon_1 \ + \epsilon_2 \ a \ \gamma^{\frac{\mu_3}{1+\mu_3}} x^{\frac{1}{1+\mu_3}}\right]^2}$$

Since $J(x)$ is strictly increasing for $x > 0$, $J(0) = 0$ and $\lim_{x \to +\infty} J(x) = +\infty$, there exists a unique x^* such that $\Psi_2'(x) \geqslant 0$ for all $x \leqslant x^*$, while $\Psi_2'(x) \leqslant 0$ for all $x \geqslant x^*$. Finally, we have $\Psi_2'(0) = \frac{1}{(1-\alpha)}$.

1.5.2 Appendix 2: Proof of Proposition 1

Existence of two steady states

We have $\lim_{x \to +\infty} \Psi_1(x) = +\infty$ and $\Psi_2(0) = 0$. Furthermore, when β tends to 0 (but stays strictly positive), $\Psi_1(0)$ and $\lim_{x \to +\infty} \Psi_2(x)$ become arbitrarily close to 0. Finally, $\Psi_2'(0) = \frac{1}{(1-\alpha)} > 1$, while $\Psi_1'(0) = \frac{1}{A}\frac{1}{s}\left(1 + \frac{1}{\epsilon_1}\right)\left(\frac{1}{A}\beta(1-\alpha)\right)^{\frac{1-s}{s}}$ tends to 0 when β tends to 0. Since $\Psi_1(x)$ and $\Psi_2(x)$ are continuous functions, we deduce that there are two solutions satisfying $\Psi_1(x) = \Psi_2(x)$ (See also Figure 1.5). By continuity, there exist two steady states for β sufficiently low, namely (x_1, k_1) and (x_2, k_2).

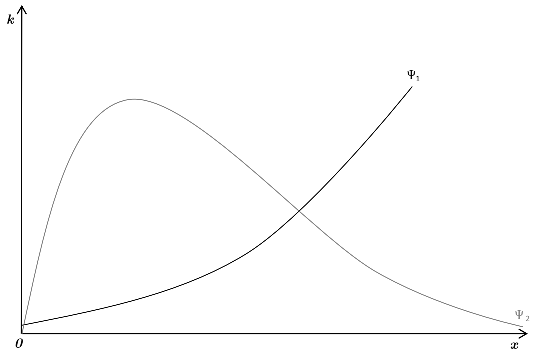


Figure 1.5: Representation of $\Psi_1(x)$ et $\Psi_2(x)$ when $\beta \to 0$

Main features of the steady states:

To fix ideas, consider that $x_1 < x_2$. Since $\Psi_1(x)$ is strictly increasing, we have $k_1 < k_2$. Recalling that $g(x)$ is decreasing and $h(x)$ is increasing, we deduce that $\Pi_2 < \Pi_1$ and $c_2 > c_1$.

According to (1.1), we have:

$$\frac{P_{t+1}}{P_t} = (1 - \alpha) + \frac{aN_t c_t}{P_t} \tag{1.15}$$

At steady state, Π_t is constant, which means that pollution and population grow at the same rate, n. Thus, equation (1.15) rewrites:

$$n = (1 - \alpha) + \frac{ac_t}{\Pi_t} \tag{1.16}$$

Since $c_2 > c_1$ and $\Pi_2 < \Pi_1$, we get $n_2 > n_1$.

Using $N_0 = 1$, $N_t = n^t$ on a steady state. We can therefore rewrite (1.16) as:

$$n = (1 - \alpha) + \frac{an^t c_t}{P_t}$$

$$\Leftrightarrow P_t = \frac{a\, n^t c_t}{n - 1 + \alpha}$$

Because Π_t and c_t are strictly positive, we have $n > 1 - \alpha$ (See (1.16)). We deduce that $P_{2t} > P_{1t}$.

1.5.3 Appendix 3: Proof of Proposition 2

To prove this proposition, we construct the phase diagram associated to the dynamic system (1.12). See also Figure 1.2. The second equation of the system (1.12) is equivalent to $\frac{x_t}{k_{t+1}} = \frac{(1-\alpha)g(x_{t-1})+a\,h(x_t)}{g(x_t)}$. Therefore, the first equation of (1.12) can be rewritten as:

$$k_t = \left[\frac{1}{A}h(x_t) + x_t + \beta\frac{(1-\alpha)g(x_{t-1}) + a\,h(x_t)}{g(x_t)}\right]^{\frac{1}{s}} \tag{1.17}$$

i.e. k_t can be written as a function of x_t and x_{t-1}: $k_t \equiv \Theta_1(x_t, x_{t-1})$, where Θ_1 is increasing in the first argument and decreasing in the second one. Note that $\Theta_1(x_t, x_t)$ is the phases line $\Delta x_{t-1} = 0$, and corresponds to the curve $\Psi_1(x_t)$, relevant for the steady state analysis. We also have:

$$x_t > x_{t-1} \Leftrightarrow \Theta_1(x_t, x_{t-1})_{|x_t > x_{t-1}} > \Theta_1(x_t, x_{t-1})_{|x_t = x_{t-1}}$$

Therefore, when k_t is above (below) $\Theta_1(x_t, x_t)$, we get $x_t > x_{t-1}$ ($x_t < x_{t-1}$).

Now, using (1.17), we implicitly define $x_t \equiv \Theta_3(k_t, x_{t-1})$, where Θ_3 is increasing in both arguments. Substituting this in the second equation of (1.12), we obtain:

$$k_{t+1} = \frac{\Theta_3(k_t, x_{t-1}) \quad g(\Theta_3(k_t, x_{t-1}))}{(1-\alpha)g(x_{t-1}) + a\,h(\Theta_3(k_t, x_{t-1}))} \equiv \Theta_2(k_t, x_{t-1}) \tag{1.18}$$

where Θ_2 is increasing in x_{t-1} at least for x_{t-1} not too large. When $k_{t+1} = k_t$, equation

(1.18) becomes:

$$k_t = \frac{\Theta_3(k_t, x_{t-1}) \quad g(\Theta_3(k_t, x_{t-1}))}{(1-\alpha)g(x_{t-1}) + a\ h(\Theta_3(k_t, x_{t-1}))} \tag{1.19}$$

which implicitly defines k_t as a function of x_{t-1}. Using that Θ_2 is increasing in x_{t-1},[22] a raise of x_{t-1} above its level defined in (1.19) implies:

$$\theta_2(k_t, x_{t-1}) > k_t \Leftrightarrow k_{t+1} > k_t$$

Thus, when x_{t-1} is below the locus $k_{t+1} = k_t$, $k_{t+1} > k_t$, whereas above this second phase line, $k_{t+1} < k_t$. Using all these elements, we can construct the phase diagram drawn in Figure 1.2 and deduce Proposition 2.

[22]This may require that x_{t-1} is not too large.

CHAPTER 2

Environmental Policy and Growth when Environmental Awareness is Endogenous

2.1 Introduction

One of the main questions raised by the literature on the link between economic growth and the environment[2], is how environmental policy can be used to attain sustainable development, where economic growth is compatible with environmental conservation. To achieve such a goal, policy makers have several economic policy instruments. The most obvious are pollution taxation and public pollution abatement (e.g. water treatment, waste management, investment in renewable energy, conservation of forests...), introduced to reduce the impact of economic activities on the environment. But governments may also invest in another type of policy tools that aim to affect the environment only by modifying households' behavior. In this regard, education, by raising environmental consciousness, can be used as an indirect intervention to protect the environment. This idea is largely supported by international organizations. For example, the United Nations declare the decade 2005-2014 to be the "UN Decade of Education for Sustainable Development"[3], while the OECD (2008) refers to education as "one of the most powerful tools for providing individuals with the appropriate skills and com-

This paper is a joint work with Marion Davin.

[2]See Brock & Taylor (2005) and Xepapadeas (2005) for literature reviews on this relationship.

[3]See resolution 57/254 of United Nations General Assembly of 2002.

petencies to become sustainable consumers". In addition to state that education is a prerequisite for sustainable development, the European Commission (2005) underlines also the role of combining several policy levers to meet this challenge. This point of view is shared by the OECD (2007, 2010), which emphasizes that instruments are likely to mutually reinforce each other. In particular, it appears that pollution taxation may not have the expected returns without complementary actions focusing on households' behavior. However, despite the growing interest in such environmental policy scheme especially by international orgnizations, no theoretical study has examined its consequences. Thus, the purpose of this paper is to investigate how an environmental policy, that combines possibly pollution taxation, pollution abatement and education support, affects economic activities and the environment.

In studying policies directed to consumers' behavior, it is especially relevant to consider the role of agents' preferences for the environment, which determine how they respond to pollution. The empirical literature highlights that these preferences evolve over time and change with economic and environmental contexts (see e.g. Dunlap & Scarce , 1991; European Commission , 2008 or Scruggs & Benegal , 2012). With this in mind, we examine the consequences of environmental policies on growth by taking into account the endogeneity of individual green preferences.

In the literature on the link between environmental policy and growth, some papers consider the role of human capital accumulation. However, they ignore the possible effects of education on agents green behavior. For example, Gradus & Smulders (1993) conclude that an improvement in environmental quality has no effect on long-term growth, except when pollution directly affects human capital accumulation. More recently, Grimaud & Tournemaine (2007) or Pautrel (2014) find that a tighter environmental tax can favor education and hence growth in the long run. The mechanism stems from the fact that the tax makes polluting activities less attractive compared to a human-capital intensive sector.

We depart from these contributions in three major ways. First, we assume that agents' preferences for the environment are endogenous. More precisely, we consider that both the individual human capital and the level of pollution affect green preferences positively, as supported by the literature. A wide range of empirical studies identifies education as an important individual determinant of environmental preferences (see Blomquist & Whitehead , 1998; Witzke & Urfei , 2001 or European Commission , 2008). The intuition is that the more educated an agent is, the more she is informed about environmental issues, and the more she can be concerned about environmental protection. In addition, pollution is also viewed as an important determinant of agents' environmental action. Environmental issues, such as climate change or air pollution, harm welfare[4] and push households to realize the extent of the problem and hence to react (see e.g. Dunlap & Scarce , 1991; Schumacher , 2009 or Schumacher & Zou , 2013). Considering an endogenous environmental awareness, our analysis is related to the recent contribution of Prieur & Bréchet (2013), who are the first to consider that green preferences depend on human capital. The authors emphasize that the economy may be caught in a steady state without economic growth, whereas public education can be used to achieve an asymptotic balanced growth path with sustainable growth. Here, we extend this paper considering that education choices are not exogenous but stem from paternalistic altruism and that environmental preferences are driven by both human capital and pollution.[5]

Second, we contribute to the literature by analyzing the effect of an environmental policy with possible "instruments mix" on growth and the environment, in line with the recommendations of international organizations. More precisely, we consider that the government can implement a tax on pollution and recycle the tax revenue in two

[4]Among other channels, pollution affects agents' well-being by damaging their health status (through mortality and morbidity) and by depreciating the environmental quality bequeathed to their children.

[5]For a paper considering the effect of environmental quality on green concerns, see Schumacher & Zou (2013). Nevertheless, they assume that environmental quality has a discrete impact on preferences.

types of environmental support: a public pollution abatement and an education subsidy. While the former represents an investment in environmental protection, the latter aim to modify green preferences.

Third, while the economic implications of environmental policies are generally studied in the long run, we also investigate its consequences in the short run. Indeed, Zhang (1999) underlines that the short-term analysis represents a crucial issue. He shows that the dynamics of an overlapping generations model with the environment can be non-linear because two opposing forces balance each other toward a sustainable steady state: agent's consumption hurts environmental quality while maintenance activities improve it. This complex dynamics raises that environmental policy can be required to smooth convergence. Ono (2003) confirms the importance of examining both the short- and long-term implications of policy, by showing that an increase in the tax can remove fluctuations, while it has a non-monotonous impact on growth in the long run according to its level. Despite the important properties identified by these authors, they do not consider the role of human capital nor environmental policy mix.

To examine such an environmental policy mix when environmental awareness is endogenous, we develop an overlapping generations model with environmental quality, where growth is driven by human capital accumulation. Human capital depends on education spending chosen by altruistic parents, while the law of motion of the environment is in line with John & Pecchenino (1994). Production creates pollution flow, which damages environmental quality, whereas abatement activities improve it. To properly represent consumer's environmental preferences, we use impure altruism *à la* Andreoni (1990), where pollution abatement is triggered by two different incentives: the level of environmental quality and the contribution itself to environmental protection. As a result, public and private contributions are not perfect substitutes, which allows us to consider an environmental policy with public maintenance. In addition, such impure altruism and its policy implications are in line with empirical evidence (see e.g. Ribar & Wilhelm , 2002; Menges *et al.* , 2005 or Crumpler & Grossman , 2008).[6]

With the present model, the economy can converge to a balanced growth path (hereafter BGP), corresponding to a sustainable development where both environmental quality and human capital grow. Depending on the share of government expenditure for public maintenance and on the level of the tax, agents can stop investing in private environmental protection at the BGP. Reversely, when they invest in private pollution abatement at the BGP, we find that endogenous concerns may generate damped oscillations. The reason is that when households' environmental awareness is highly sensitive to a green development index, the feedback effect of human capital and environmental quality on green preferences affects significantly their trade-off between education and maintenance choices, which causes oscillations. This complex dynamics leads to significant variations in the levels of human capital and environmental quality across generations, and hence to variations in terms of welfare. Therefore, it corresponds to intergenerational inequalities along the convergence path that represent a challenge for policy makers.

We study the effect of the policy in both the short and long run, and investigate whether it can allow the economy to avoid intergenerational inequalities and boost its long-term growth rate. We do not compute a welfare analysis, which is not analytically tractable in our setting, but we give intuitions about the economic impacts of environmental policy. In particular, we emphasize that an increase in the tax can enhance growth and remove inequalities as long as the tax revenue is well allocated. This win-win situation is achieved for an intermediary allocation of the budget between public maintenance and education subsidy, that ensures the convergence of the economy to a BGP where households do not invest in private maintenance and the level of education is

[6]In other words, when the government increases spending for the public good, there is not a complete crowding out effect on private contribution. Ribar & Wilhelm (2002) and Crumpler & Grossman (2008) look at charitable giving, while Menges *et al.* , 2005 focus on environmental contribution.

sufficiently high. Indeed, in this case, environmental maintenance is entirely supported by public authorities, such that households' behaviors are less dependent on economic and environmental context and intergenerational inequalities do not occur. Moreover, this policy also translates into a higher sustainable rate of growth. The reason is that the budget devoted to the environment is sufficiently high to remove private maintenance in spite of the agents' joy of contributing, meaning that environmental quality is good enough. At the same time, the high share of public support in education enables the positive effect of the education subsidy to offset the negative impact of the tax on available income. Thus, we conclude that the implementation of an environmental policy mix can be suitable to address short- and long-term environmental issues.

The paper is organized as follows. In Section 2, we set up the theoretical model. Section 3 focuses on the BGP and the transitional dynamics. In Section 4, we examine short- and long-term implications of environmental policy. Finally, Section 5 concludes. Technical details are relegated to an Appendix.

2.2 The model

Consider an overlapping generations economy, with discrete time indexed by $t = 0, 1, 2, ..., \infty$. Households live for two periods, childhood and adulthood, but take all decisions during their second period of life. At each date t, a new generation of N identical agents is born ($N > 1$). We assume no population growth.

2.2.1 Consumer's behavior

Individuals born in $t-1$ care about their levels of consumption c_t and of environmental quality Q_t when adult. Through paternalistic altruism, they value the human capital of their children h_{t+1}, such that parents finance children's education (as in Glomm & Ravikumar , 1992). Finally, they also have altruistic preferences for the environment. As environmental quality is a public good, we follow arguments advanced by the behavioral economics literature, which attempts to identify the motives for private contribution to this kind of good. Both theoretical and empirical studies suggest that such contribution, including investment in environmental protection, arises from an "impure altruism" (e.g. Ribar & Wilhelm , 2002; Menges *et al.* , 2005 or Crumpler & Grossman , 2008).[7] In this way, there are two motives for private environmental action: a "pure altruism" for the level of environmental quality bequeathed to their children (i.e. the future environmental quality Q_{t+1}) and a "joy of giving" for the act of contributing itself (i.e. environmental maintenance m_t). In addition to properly represent environmental preferences, the formalization of impure altruism is important for studying environmental policy. The reason is that with the "joy of giving" for maintenance, public and private contributions are not perfect substitutes (see Andreoni , 1990).

Preferences of a representative agent, born in $t-1$, are represented by the following utility function:

$$U(c_t, m_t, h_{t+1}, Q_{t+1}) = \ln c_t + \gamma_{1t} \ln(\varepsilon_1 \, m_t + \varepsilon_2 \, Q_{t+1}) + \gamma_2 \ln h_{t+1} + \gamma_3 \, \ln Q_t \quad (2.1)$$

with γ_{1t}, γ_2, γ_3, ε_1 and $\varepsilon_2 > 0$.

The parameters γ_3 and γ_2 capture the usual taste for current environmental quality and the preference for her child's human capital, respectively.[8]

The weight γ_{1t} captures the environmental awareness. We consider that these environmental preferences are affected negatively by the level of environmental quality (Q_t) and positively by the individual human capital (h_t), as supported by the literature.[9] Pollution, by affecting welfare, has an impact on environmental behaviors: when

[7]This formalization is not relevant for human capital, as it is a private good.

[8]Current environmental quality is not related with altruism concerns and is taken as given by agents, as they have no impact on the current level of environmental quality.

[9]In this paper, we consider pollution as the opposite of the environmental quality index Q. Thus, we will use both concepts interchangeably.

pollution is high, agents are more likely to be concerned by the environment and to act in favor of it, as underlines Dunlap & Scarce (1991) or Schumacher (2009). The worst environmental quality, the more the individual is able to realize the badness of the situation and therefore the more she has an incentive to protect the environment. Reversely, a better environmental quality may reduce the willingness to improve the environment and hence imply a slackening of efforts, as it appears less necessary. At the same time, the empirical behavioral economics literature identifies education as a determinant of the contribution to the environment (see Blomquist & Whitehead , 1998 or Witzke & Urfei , 2001). The economic intuition is that the more an agent is educated, the more she may be informed about environmental issues and their consequences, and thus the more she can be concerned about it. We assume that $\gamma_{1t} = \gamma_1(h_t, Q_t)$ where γ_1 is increasing and concave with respect to h, and decreasing and convex with respect to Q.[10] For tractability reasons, we consider the following functional form, in line with the form commonly used to represent endogenous longevity, defined as the weight of future arguments in the utility function (see e.g. Blackburn & Cipriani , 2002).

$$\gamma_{1t} \equiv \frac{\beta h_t + \eta Q_t}{h_t + Q_t} \tag{2.2}$$

with parameters β, $\eta \in [0,1]$ and $\beta \geqslant \eta$. The parameters β and η embody respectively the weight of human capital and of environmental quality in green preferences. Let us underline that when $\beta = \eta$, the environmental awareness is constant.

During childhood, individual does not take decisions. She is reared by her parents and benefits from education. When adult, she supplies inelastically one unit of labor remunerated at the wage w_t according to her human capital level h_t. She allocates this

[10]With this properties, extreme behaviors are excluded. The effects of pollution and human capital are positive but become less and less important as their levels increase. Moreover, the effect of the variation of h on the absolute value of the impact of Q on γ_1 is equal to: $\frac{\partial}{\partial h_t}|\frac{\partial \gamma_{1t}}{\partial Q_t}| = \frac{(\beta-\eta)(Q_t-h_t)}{(h_t+Q_t)^3}$, so that agents react less to the variation of pollution when their level of human capital is very low or very high. The reason is respectively that they have not the mean to be concerned about pollution when they have a low h, and that they are already highly concerned with environmental issues when h is high.

income to consumption c_t, education per child e_t and environmental maintenance m_t.[11] Furthermore, as environmental awareness depends on human capital, authorities can use education support as an environmental policy lever. In this sense, we consider that the government can subsidize education at the rate $0 \leqslant \theta_t^e < 1$ with the revenue of a pollution tax that we will present later. This policy reduces the private cost of education, such that the budget constraint for an adult with human capital h_t is:

$$c_t + m_t + e_t(1 - \theta_t^e) = w_t h_t \tag{2.3}$$

The human capital of the child h_{t+1} is produced with the private education expenditure e_t and the human capital of the parents h_t:

$$h_{t+1} = \epsilon \; {e_t}^{\mu} {h_t}^{1-\mu} \tag{2.4}$$

with $\epsilon > 0$, the efficiency of human capital accumulation. The parameter $0 < \mu < 1$ is compatible with endogenous growth and captures the elasticity of human capital to private education, while $1 - \mu$ represents the share of human capital resulting from intergenerational transmission within the family.

The law of motion of environmental quality is defined by:

$$Q_{t+1} = (1 - \alpha)Q_t - aY_t + b(m_t + M_t + NG_t^m) \tag{2.5}$$

where $\alpha > 0$ is the natural degradation of the environment and Y_t represents the pollution flow due to production in the previous period. The parameter $a > 0$ corresponds to the emission rate of pollution, while $b > 0$ is the efficiency of environmental maintenance. The abatement activities are represented by a Cournot-Nash equilibrium approach. Each

[11]See Kotchen & Moore (2008) for empirical evidences of private provision of environmental public goods.

agent determines her own environmental maintenance (m_t), taking the others' contribution (M_t) as given.[12] The government can also use the revenue of the pollution tax to directly improve environmental quality, by providing a public environmental maintenance $NG_t^m \geqslant 0$. Note that the efficiency of the public maintenance is the same as the private environmental protection. Following the seminal contribution of John & Pecchenino (1994), Q is an environmental quality index with an autonomous value of 0 in the absence of human intervention. More precisely, this index embodies the local environmental quality percieved by agents and corresponds to the amenity value of the environment, derived for example from the quality of air, water and soil, from the resource availability or from national parks.[13]

The consumer program is summarized by:

$$\max_{e_t, m_t}, U(c_t, m_t, h_{t+1}, Q_{t+1}, Q_t) = \ln c_t + \gamma_{1t} \ln(\varepsilon_1 \; m_t + \varepsilon_2 \; Q_{t+1}) + \gamma_2 \ln h_{t+1} + \gamma_3 \; \ln Q_t \quad (2.6)$$

$$s.t \quad c_t + m_t + e_t(1 - \theta_t^e) = w_t h_t$$

$$h_{t+1} = \epsilon \; {e_t}^{\mu} {h_t}^{1-\mu}$$

$$Q_{t+1} = (1-\alpha)Q_t - aY_t + b(m_t + M_t + NG_t^m)$$

with $m_t \geqslant 0$.

2.2.2 Production

Production of the consumption good is carried out by a single representative firm. The output is produced according to a constant returns to scale technology:

$$Y_t = AH_t \quad (2.7)$$

[12] More precisely, for each agent j, the maintenance of others corresponds to $M_t = \sum_k m_{kt} \; \forall k \neq j$.

[13] We consider $Q > 0$, which is a standard assumption (see e.g. Ono , 2003 or Mariani *et al.* , 2010).

where H_t is the aggregate stock of human capital and $A > 0$ measures a technology parameter.

Since pollution is a by-product of the production process, human capital exerts two opposite effects on the environment: a positive one through awareness that motivates environmental protection, and a negative one through the increase in quantities produced, that raises the amount of waste and pollution emissions. Therefore, even if human capital is not a highly polluant input per se, it defines the scale of production and hence of emissions.[14] In order to keep the analysis tractable and to focus on the mechanisms linked to human capital, we consider that the only input in the production function is the aggregate human capital, while the share of polluting factors in the production process is constant and represented by the paramater A.[15] Therefore, the polluting production process is composed of an index of pollution intensity A and of the level of human capital determining the scale of pollution emissions.

Defining $y_t \equiv \frac{Y_t}{N}$ as the output per worker and $h_t \equiv \frac{H_t}{N}$ as the human capital per worker, we have the following production function per capita:

$$y_t = Ah_t \tag{2.8}$$

The government collects revenues through a tax rate $0 \leqslant \tau < 1$ on production, which is the source of pollution. The firm chooses input to maximize its profit $(1-\tau)Y_t - w_t H_t$, such that :

$$w_t = A(1-\tau) \tag{2.9}$$

[14]Note that it seems realistic as regards high-income economies where individuals have globally higher green preferences than low-income countries, but also where, for example, the ecological footprint per capita is about five times higher than that of low-income countries (WWF , 2014).

[15]Introducing physical capital accumulation, for example, would make the analysis much more complex, as it adds a new dimension in the dynamics.

2.2.3 The government

The design of environmental policy represents a major challenge for governments. Among other reports, OECD (2007, 2008) recommends the revenue recycling of tax on polluting activities in order to complete the action of the government. This kind of policy is observable in several countries. For example, in France, the government implements a general tax on polluting activities (TGAP) and transfers revenues to the French Environment and Energy Management Agency (ADEME) that funds activities in favor of the environment. To achieve environmental objectives, policy makers have several economic levers. They can implement policies that directly affect the environment (e.g. conservation of forests and soils, water treatment, waste management), but also more indirect policies that affect the environment only by modifying green behaviors. As we underlined in the Introduction, international organizations widely support this latter kind of tools to achieve a sustainable development. More precisely, they underline that education may favor the environment through the increase in environmental awareness it generates. Therefore in this paper, we will consider such an educational policy implemented to raise awareness among our set of environmental tools. However, note that, even if the purpose of the education support is here to increase green preferences which pushes agents to invest in environemental protection, it has also a negative effect on the environment by increasing the scale of polluting production.

More precisely, we consider the following policy scheme in this model: since pollution is a by-product of the production process, the government taxes the output at rate τ and the public budget is spent on public environmental maintenance NG_t^m or/and on education subsidy θ_t^e. The government's budget is balanced at each period, such that:[16]

[16] In order to standardize notations, we express both education subsidy and public maintenance in per capita terms, hence G_t^m is the amount of public maintenance per capita.

$$N(\theta_t^e e_t + G_t^m) = \tau Y_t \tag{2.10}$$

To study possible policy mix in a simple way, we define the constant share of public expenditure devoted to the public maintenance $0 \leqslant \sigma \leqslant 1$, and respectively the share devoted to the education subsidy $(1-\sigma)$,

$$\sigma = \frac{NG_t^m}{\tau Y_t} \;\; ; \;\; 1-\sigma = \frac{N\theta_t^e e_t}{\tau Y_t} \tag{2.11}$$

such that the fiscal policy is summarized by two instruments: the pollution tax τ and the allocation of public revenue σ, both taken as given by consumers.

2.2.4 Equilibrium

The maximization of the consumer program (2.6) leads to the optimal choices in terms of education and maintenance in two regimes: an interior solution, where individuals invest in environmental protection $m_t > 0$ (hereafter *pm*) and a corner solution without private contributions to the environment $m_t = 0$ (hereafter *npm*). The Nash intertemporal equilibria are given by:

$$m_t = \begin{cases} \frac{\gamma_{1t} c_1 A h_t (1-\tau) - \varepsilon_2 (1+\gamma_2\mu)[(1-\alpha)Q_t + ANh_t(b\sigma\tau - a)]}{\gamma_{1t} c_1 + c_2 + \varepsilon_2 bN(1+\gamma_2\mu)} & pm \\ 0 & npm \end{cases} \tag{2.12}$$

$$e_t = \begin{cases} \frac{\gamma_2\mu[c_3 A(1-\tau)h_t + \varepsilon_2((1-\alpha)Q_t + ANh_t(b\sigma\tau - a))]}{\gamma_{1t} c_1 + c_2 + \varepsilon_2 bN(1+\gamma_2\mu)} + (1-\sigma)\tau A h_t & pm \\ \frac{Ah_t[\gamma_2\mu(1-\tau) + \tau(1-\sigma)(1+\gamma_2\mu)]}{1+\gamma_2\mu} & npm \end{cases} \tag{2.13}$$

where c_1, c_2 and c_3, three positive constants defined by $c_1 \equiv \varepsilon_1 + \varepsilon_2 b$; $c_2 \equiv \varepsilon_1(1 + \gamma_2\mu)$ and $c_3 \equiv \varepsilon_1 + \varepsilon_2 bN$.[17]

Education spending depends positively on environmental quality. The better the environment, the lower the optimal amount of maintenance activities. As a result, education becomes more attractive and individuals can devote more resources in educating their children.

Moreover, the public policy instruments shape education and abatement spendings differently. An increase in the tax implies a negative income effect (wage decreases) but still favors education spending when the share of public expenditure in the education subsidies is sufficiently high (σ low).[18] However, an increase in the tax always affects negatively maintenance activities. In addition to the negative income effect, the tax increases the public pollution abatement, which crowds out the private maintenance. Nevertheless, the public spending substitutes only partially to the private one due to the joy of giving motive in utility function.

Remark 3 *Without a joy-of-giving motive for the environment (i.e. $\varepsilon_1 = 0$):*

- *If all public expenditure were devoted to pollution abatement ($\sigma = 1$), there would be a total crowding-out of private maintenance such that the environmental policy would have no effect on the environment.*

- *If the budget were allocated to the two types of expenditure ($\sigma < 1$), the fall in private maintenance would outweigh the increase in public maintenance. Consequently, the overall maintenance would decrease with the environmental policy.*

Such a configuration is in contradiction with the empirical and experimental literature which only recognizes a partial crowding-out of private contribution by government expenditure.[19] *Therefore, the joy-of-giving motive (ε_1) is necessary for a meaningful policy*

[17] See details in Appendix 2.6.1.

[18] $\frac{\partial e_t}{\partial \tau} > 0$ $\left(resp.\ \frac{\partial e_t}{\partial \tau} < 0\right)$, when $\sigma < \frac{\gamma_{1t}c_1 + c_3}{\gamma_{1t}c_1 + c_3 + \varepsilon_1\gamma_2\mu}$ $\left(resp.\ 1 \geqslant \sigma > \frac{\gamma_{1t}c_1 + c_3}{\gamma_{1t}c_1 + c_3 + \varepsilon_1\gamma_2\mu}\right)$.

[19] See e.g. Ribar & Wilhelm (2002), Menges *et al.* (2005) or Crumpler & Grossman (2008).

analysis in our setting.

Studying endogenous growth, we write the environment in an intensive form, by considering environmental quality per unit of human capital $\frac{Q_t}{h_t} \equiv X_t$. This ratio enables to capture the evolution of the environment compared to the development of economic activities. For the rest of the analysis, we define X_t as a green development index. Thus, the environmental awareness, given by (2.2), can be rewritten:

$$\gamma_{1t} = \frac{\beta + \eta X_t}{1 + X_t} \tag{2.14}$$

Using equations (2.12) and (2.14), we emphasize that households invest in environmental protection for:

$$X_t \leqslant \frac{A\left[\frac{(\beta+\eta X_t)c_1(1-\tau)}{1+X_t} - \varepsilon_2 N(1+\gamma_2\mu)(b\sigma\tau - a)\right]}{\varepsilon_2(1+\gamma_2\mu)(1-\alpha)} \tag{2.15}$$

From this inequality, we deduce that there exists a critical threshold $\Lambda(\sigma,\tau) \geqslant 0$ such that environmental protection is privately supported as long as:[20]

$$X_t \leqslant \Lambda(\sigma,\tau) \tag{2.16}$$

When this inequality is unsatisfied ($X_t > \Lambda(\sigma,\tau)$), the level of environmental quality is so high and/or the level of human capital so low, that the private abatement of pollution is given up. The critical threshold $\Lambda(\sigma,\tau)$ is decreasing in the tax on pollution τ and in the share of public spending devoted to environmental maintenance σ. Therefore, when the government intervenes, the economy is more likely to be characterized by no maintenance activities since the public maintenance partially substitutes for the private one. This result still holds if the revenue recycling is entirely devoted to education because agent

[20]See technical details in Appendix 2.6.1.

replaces some abatement activities by education, as the latter becomes relatively less costly. Reversely, the higher green preferences, the higher the level of environmental quality for which the agent decides not to support environmental protection (the higher the critical threshold $\Lambda(\sigma, \tau)$).

Using the human capital accumulation (2.4), the environmental quality process (2.5), and the first order conditions (2.12) and (2.13), we write the dynamical equation characterizing equilibrium paths:

Definition 3. *Given the initial condition* $X_0 = \frac{h_0}{Q_0} > 0$, *the intertemporal equilibrium is the sequence* $(X_t)_{t\in\mathbb{N}}$ *which satisfies, at each* t, $X_{t+1} = \mathcal{F}(X_t)$, *with:*

$$\mathcal{F}(X_t) = \begin{cases} \frac{(1-\alpha)\ X_t\ [\gamma_{1t}\ c_1+c_2]+AN\ [\gamma_{1t}\ c_1 b(1-\tau)+(\gamma_1 c_1+c_2)(b\tau\sigma-a)]}{\epsilon[\gamma_2\mu A\ c_3(1-\tau)+\gamma_2\mu\varepsilon_2[(1-\alpha)X_t+AN(b\sigma\tau-a)]+(1-\sigma)\tau A(\gamma_{1t}\ c_1+(1+\gamma_2\mu)c_3)]^{\mu}[\gamma_{1t}\ c_1+(1+\gamma_2\mu)c_3]^{1-\mu}} & pm \\ \frac{(1-\alpha)X_t+AN(b\sigma\tau-a)}{\epsilon\left[\frac{\gamma_2\mu A(1-\tau)+(1-\sigma)\tau A(1+\gamma_2\mu)}{1+\gamma_2\mu}\right]^{\mu}} & npm \end{cases} \tag{2.17}$$

2.3 Balanced growth path and transitional dynamics

We examine in this section the existence of a BGP equilibrium characterized as:

Definition 4. *A balanced growth path (BGP) satisfies Definition 1 and has the following additional properties: the stock of human capital and environmental quality grow at the same and constant rate* g_i, *with subscripts* $i = \{pm, npm\}$ *denoting respectively the regime with Private Maintenance and the regime where there is No Private Maintenance. This equilibrium path is such that the green development index* X_t *is constant and defined by* $X_{t+1} = X_t = \bar{X}_i$.

From Definitions 3 and 6 and equations (2.14) and (2.16), we emphasize the properties of the dynamical equation $\mathcal{F}$ and deduce the existence of a BGP $\bar{X}_i$ corresponding to the solutions of equation $\bar{X}_i = \mathcal{F}(\bar{X}_i)$:

Proposition 4. *When $\beta > \eta$ and $\sigma_{Min}(\tau) < \sigma < \sigma_{Max}(\tau)$ for all $\tau \in [0,1)$, there exists a unique positive BGP $(\bar{X}_i)$, such that, according to a critical threshold $\hat{\sigma}(\tau)$:*

- *When $\sigma > \hat{\sigma}(\tau)$, the BGP is in the regime without private maintenance (npm).*
- *When $\sigma < \hat{\sigma}(\tau)$, the BGP is in the regime with private maintenance (pm).*

where $\sigma_{Min}(\tau) \equiv \frac{a(\beta c_1+c_2)-b\beta c_1(1-\tau)}{b\tau(\beta c_1+c_2)}$, $\sigma_{Max}(\tau) \equiv \frac{A(\gamma_2\mu+\tau)-\epsilon^{-1/\mu}(1+\gamma_2\mu)(1-\alpha)^{1/\mu}}{A\tau(1+\gamma_2\mu)}$ and $\hat{\sigma}(\tau)$ is a decreasing function of τ, with $\lim_{\tau\to 0}\hat{\sigma}(\tau) = +\infty$ and $\lim_{\tau\to 1}\hat{\sigma}(\tau) = a/b$.

Proof. See Appendix 2.6.2. ■

The balanced growth path corresponds to a sustainable development, where both human capital and environmental quality improve across generations. The existence of such a long-term sustainable development depends on several conditions, sum up in Proposition 4 by $\sigma_{Min}(\tau) < \sigma < \sigma_{Max}(\tau)$ for all $\tau \in [0,1)$. First, it implies that human capital accumulation and environmental maintenance have to be sufficiently efficient. In particular, the efficiency of environmental protection has to be higher than the weight of pollution flow in environmental quality ($b > a$). Thus, a prerequisite to obtain a sustainable development is that the environmental benefit from one unit of maintenance is higher than the environmental damage from one unit of production. Here, it seems reasonable as the environmental quality that we consider is the one perceived by agents. Therefore, their abatement activities are most likely to focus on what matters for them and hence to be efficient. Moreover, maintenance activities are devoted to the improvement of the environment, while pollution is a side-effect of the aggregate production process.

Second, extreme allocations of public revenue are excluded for high levels of the tax. The reason is that when the tax rate is high, the agent's available income is very low. Then, for extreme allocations of public spending, toward education subsidy or environmental maintenance, one of the two actions driving sustainable development is highly disadvantaged (too expensive and not publicly supported). Thus, in order to achieve a state where both the environment and economic activity improve, the government has to allocate correctly its public budget when the tax is high, while all allocations are acceptable when the tax is low. Furthermore, for the sustainable balanced growth path to exist in the regime without maintenance, the possible policy scheme are restricted. Indeed, the condition that guarantees that the long-term equilibrium is in this regime, $\sigma > \hat{\sigma}(\tau)$, implies that $b\sigma\tau > a$ such that overall effect of economic activity on the environment is positive. In other words, a long-term equilibrium without private maintenance can be sustainable only if the public support to the environment is sufficiently high. For the rest of the paper, we assume the condition of Proposition 4 to be true:[21]

Assumption 1. *For all* $\tau \in [0, 1)$*, we assume that* $\sigma_{Min}(\tau) < \sigma < \sigma_{Max}(\tau)$*.*

The policy makes possible that a sustainable BGP without private abatement exists. If the share of public spending devoted to environmental protection is sufficiently high ($\sigma > \hat{\sigma}(\tau)$), households may stop investing in private maintenance in the long run, as underlined in Proposition 4, despite their willingness to protect the environment. However, when environmental awareness (γ_1) is very high, the public effort toward the environment allowing the long-term equilibrium to be in the *no private maintenance* regime is also very high, as $\hat{\sigma}(\tau)$ increases with green preferences.

From the study of the dynamical equation, we derive the stability properties of the BGP presented in Proposition 5. When the BGP is in the *npm* regime, we obtain an explicit solution whose dynamics is easily deduced. However, to analyze the stability of the equilibrium in the *private maintenance* regime, we normalized $\bar{X}_{pm}$ to one, using the scaling parameter ϵ.

[21] If this condition does not hold, there is no balanced growth path, or the growth rate of human capital is always negative so that the economy collapses.

Proposition 5. *Under Assumption 1 and $\beta > \eta$:*

- *The BGP in the regime without private maintenance, $\bar{X}_{npm}$, is globally and monotonously stable.*
- *The BGP in the regime with private maintenance, $\bar{X}_{pm}$, is locally stable and for $N > \bar{N}(\tau, \sigma)$, there exists a $\tilde{\beta}(\tau, \sigma) \in (0, 1]$ such that:*[22]
  - *when $\beta < \tilde{\beta}(\tau, \sigma)$, the convergence is monotonous.*
  - *when $\beta \geqslant \tilde{\beta}(\tau, \sigma)$, the convergence is oscillatory.*

Proof. See Appendix 2.6.3. ∎

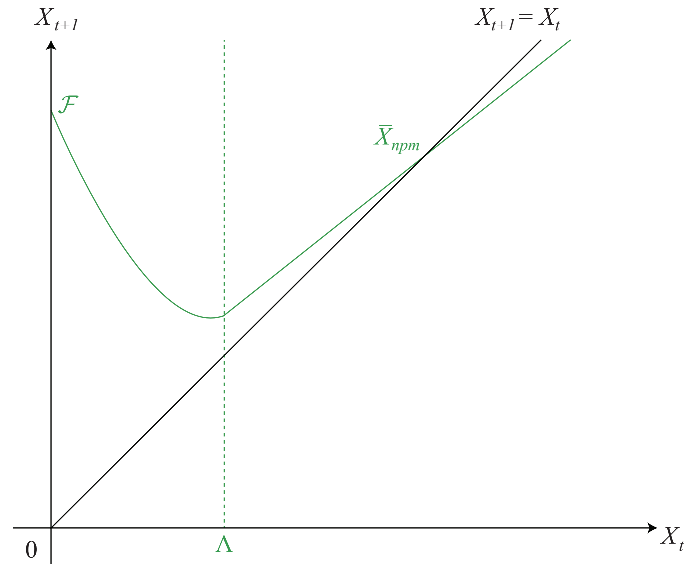
Figure 2.1 provides an illustration of the cases identified in Proposition 5.

As underlined in Proposition 5, the economy may display damped oscillations because of endogenous concerns.[23] The emergence of complex dynamics is explained by the feedback effect between green development index and environmental awareness, which affects the trade-off between education and maintenance.

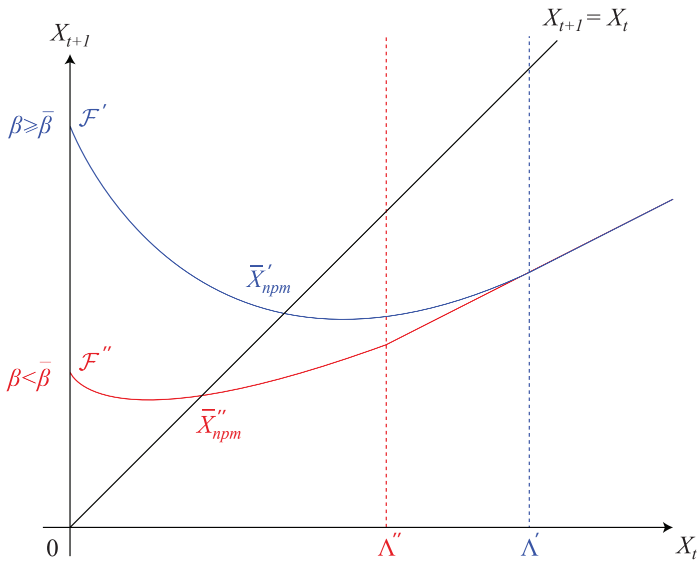
In the absence of private maintenance, this trade-off does not exist as households focus on education and the dynamics is always monotonous. Whereas when agent invests in environmental protection, cyclical convergence may occur and can be described as follows. An increase in environmental awareness γ_{1t} encourages private maintenance investment at the expense of education spending. For the next generation, it generates a fall in human capital h_{t+1}, a raise in environmental quality Q_{t+1} and hence a decrease in green preferences γ_{1t+1}. These variations entail multiple effects on the private choices. They all shape negatively private maintenance m_{t+1} whereas the impact is ambiguous for education e_{t+1}. Indeed, education spending is affected positively by the fact that

[22] The threshold $\tilde{\beta}(\tau, \sigma)$ increases with η. The effect of the policy on transitional dynamics is studied in Proposition 6 and Remark 4.

[23] At the limit case $\beta = \eta$, γ_1 is exogenous and the dynamics is always monotonous. The proof is available upon request.



(a) when $\sigma > \hat{\sigma}(\tau)$



(b) when $\sigma < \hat{\sigma}(\tau)$

Figure 2.1: Dynamics when $N > \overline{N}$

private maintenance becomes less needed (from the raise in Q_{t+1}) and less wanted (from the decrease in γ_{1t+1}), while it is affected negatively by an income effect due to the fall in human capital h_{t+1}. Thus, the opposite variation of human capital h_{t+1} acts as a brake on oscillations, i.e. a stabilizing effect, such that cyclical variations are damped. As a result, the economy displays oscillations as long as the two positive impacts on education exceed the negative income effect.

The oscillatory dynamics in preferences emerges when the population size is not too low ($N > \bar{N}$), such that individuals' behavior has a significant impact on environmental quality. In this way, when agent's preferences are highly sensitive to the green development index X (high β and low η), the environmental consciousness fluctuates.[24] This result is in line with Zhang (1999) who finds that complex dynamics may emerge in OLG model with environmental quality since agent's consumption depresses the environment while maintenance activities improves it. This author underlines that greener preferences are necessary to avoid such dynamics. Here, oscillations arise from the endogenization of environmental consciousness and the feedback effect of environment and education on green behaviors. More precisely, it occurs when the sensitivity of environmental awareness to the green development index is high, whatever the level of these preferences.

The oscillatory dynamics implies that environmental awareness (γ_1) experiences significant variations along the converging trajectory. Note that, these variations are around a trend and hence are not too extreme. Indeed, due to the fact that human capital and environmental quality are two stocks variables, there is some inertia in preferences. Moreover, in reality, there certainly exist additional effects reducing such oscillations, as some kind of irreversibility in preferences (related to habits, for instance). However, such variations in green preferences are consistent with empirical evidence. For exam-

[24]The term sensitivity of preferences to X refers alternatively to the convexity and to the elasticity of γ_1 to X: the second derivative is given by $\frac{2(\beta-\eta)}{(1+X)^3}$ and the elasticity by $\frac{-(\beta-\eta)X}{(1+X)(\beta+\eta X)}$. At a given X, oscillations occur for high elasticity or convexity.

ple, Dunlap & Scarce (1991) remind that even if they have globally increased since the late 60s, public concern for the environment has experienced fluctuations according to economic and environmental context. Likewise, Scruggs & Benegal (2012) find that the decline of public concern about climate change observed since 2008 in the United States is due to the great recession. Therefore, these studies emphasize that a rise in environmental problems leads to a substantial increase in individuals' support for environmental protection, while economic issues have the reverse effect.

The fluctuations in environmental awareness, that we find in this paper, cause variations in environmental quality and human capital across generations. It follows that some generations experience higher levels and growth rates of human capital and environmental quality than others. As Seegmuller & Verchère (2004) show, such cyclical convergence makes the welfare varies across generations and corresponds to intergenerational inequalities. The term inequality refers here to the fact that, when fluctuations emerge, the high environmental quality of some generations is obtained at the expense of others and reversely. Therefore, such complex dynamics translates into cyclical short-run growth and hence is also closely related to the concept of volatility, as Varvarigos (2011) argues. This result emphasizes the importance of studying the short-term effect of environmental policy.

2.4 Environmental policy implications

In this section, we analyze the consequences of the environmental policy on intergenerational inequalities in the short-run and on the long-term growth rate.[25]

[25] Although we do not provide a welfare analysis in this model, we discuss about the sources of non-optimality in Appendix 2.6.6.

2.4.1 The short-term effect of the environmental tax

We point out, previously, that the economy may exhibit complex dynamics when environmental awareness is endogenous. We wonder then how a tighter environmental tax affects this short-term situation and if the use of a policy mix allows to reduce intergenerational inequalities.[26] Focusing on the BGP in the *private maintenance* regime, where damped oscillations may occur, we examine the effect of an increase in the environmental tax on transitional dynamics.[27]

Proposition 6. *Under Assumption 1 and $\beta > \eta$, for a sufficient increase in the tax on pollution, σ becomes higher than $\hat{\sigma}(\tau)$. In this way, the BGP in the regime with private maintenance moves to the regime without private maintenance, where there is no oscillations.*

Proof. See Appendix 2.6.4. ■

An increase in the environmental tax makes more likely that agents do not invest privately in environmental protection at the BGP (as $\hat{\sigma}(\tau)$ goes down). The main reason is that a tighter tax allows to increase the government's budget, and hence the amount of public environmental maintenance. Moreover, the convergence to such a BGP is always monotonous. Thus, the government may avoid intergenerational inequalities by fixing a sufficiently high tax on pollution and devoting a large share of public spending to maintenance (so that $\hat{\sigma}(\tau) < \sigma$). In this way, the BGP moves to the regime where maintenance is entirely publicly funded, there is no more trade-off between private choices and hence transitional dynamics does not result in oscillations.

In the case where the level of the tax needed to achieve the regime without private maintenance is too high, it can be seen as unreasonable, due to its damaging effect on

[26] Given that the dynamical analysis is local, it applies when the economy is initially closed to the BGP. However, the convergence is not instantaneous but occurs on several periods. Thus, we consider that our dynamical study corresponds to the short-term effect of policy.

[27] A BGP initially in the *npm* regime cannot shift to the *pm* regime, following an increase in the tax.

agents' consumption. In this regard, it seems important to study the possible effects of the policy when the economy stays in the regime with private maintenance:

Remark 4 *Under Assumption 1 and $\beta > \eta$, an increase in τ which do not allow the BGP to reach the regime without private maintenance ($\sigma < \hat{\sigma}(\tau)$), there exists a $\tilde{\sigma} \in (0, 1)$ such that:*

- *For $\sigma < \tilde{\sigma}$, the cases where oscillations occur are less frequent.*
- *For $\sigma > \tilde{\sigma}$, the cases where oscillations occur may be more or less frequent.*

Proof. See Appendix 2.6.4. ■

From Remark 4, we highlight that the government intervention may also neutralize or generate damped oscillations and hence intergenerational inequalities. It comes from the fact that the policy shapes the trade-off between maintenance and education spendings, and hence the mechanism driving oscillations. As previously mentioned, this mechanism relies on the fact that education variations stem from several effects through environmental quality Q, environmental awareness γ_1 and human capital h. The former effects drive oscillations while the latter works in the reverse.

When $\sigma < \min\{\tilde{\sigma}; \hat{\sigma}(\tau)\}$, an increase in the environmental tax allows to reduce the occurrence of cases where oscillations arise. The reason is that as long as σ is low enough, public spending is sufficiently devoted to education support so that a tighter tax reinforces the impact of human capital on private education spending. Indeed, the fall in wage, entailed by the tax, is overcompensated by the increase in the education subsidy. Education spending is mainly driven by the government's action and hence become less sensitive to the variations of green preferences γ_1. As a result, oscillatory trajectories are less frequent, i.e. the condition to observe damped oscillations is stricter.

When $\tilde{\sigma} < \sigma < \hat{\sigma}(\tau)$, policy may increase the occurrence of intergenerational inequalities. The intuition is the following. Public revenue devoted to abatement σ is such that agents continue to invest in maintenance and is too high to ensure that the amount of the education subsidy prevents oscillations. Indeed, the environmental tax diminishes the influence of human capital on private education spending and oscillations may occur more frequently. Specifically, the necessary condition to observe damped oscillations is more easily satisfied.

Thus, from Proposition 6, we point out that with endogenous concerns, the environmental tax may remove intergenerational inequalities around the BGP if the product of the tax is correctly used. The implications of environmental policy in the short-run are rarely studied. A notable exception is Ono (2003), who emphasizes that a sufficient increase in the environmental tax may shift the economy from a fluctuating regime to a BGP where capital and environmental quality go up perpetually. In this paper, we highlight that the use of the tax revenue is decisive for such a change.

Our short-term analysis of the effect of environmental policy reveals that the government can play a role in avoiding fluctuations in environmental preferences that are costly in terms of equity among generations. For that, policy makers should invest sufficiently in education or in environmental protection to make households' behaviors less dependent on economic and environmental context.

2.4.2 The long-term effect of the environmental tax

In accordance with the concept of sustainable development and the famous definition given in the Brundtland Commission (WCED , 1987)[28], environmental policy attempts also to find the right balance between economic and environmental perspectives in the long run. In this respect, we want to study what solutions the government can put in place to achieve higher long-term growth of both human capital and environmental quality. Thus, we examine how policy affects the stable BGP and the corresponding

[28]The Brundtland Commission defines the sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

growth rate.

Using equations (2.4) and (2.13), the expression of the long-term growth rate is given by:

$$1+g_H = \begin{cases} \epsilon \left[\frac{\gamma_2\mu\big[A(1-\tau)c_3+\varepsilon_2\big((1-\alpha)\bar{X}_{pm}+AN(b\sigma\tau-a)\big)\big]+(1-\sigma)\tau A(\bar{\gamma_1}c_1+c_3(1+\gamma_2\mu))}{\bar{\gamma_1}c_1+(1+\gamma_2\mu)c_3} \right]^{\mu} & pm \\ \epsilon \left[\frac{A[\gamma_2\mu(1-\tau)+\tau(1-\sigma)(1+\gamma_2\mu)]}{1+\gamma_2\mu} \right]^{\mu} & npm \end{cases} \tag{2.18}$$

A tighter environmental policy influences the long-term growth rate through several channels. First directly, by affecting the trade-off between education and maintenance activities. Second indirectly, by modifying the green development index and environmental preferences.[29] Therefore, the global impact is ambiguous. In the following proposition, we emphasize how authorities can improve the growth rate along the BGP:

Proposition 7. *Under Assumptions 1 and $\beta > \eta$, following an increase in τ:*

- *When the BGP remains in the pm regime ($\sigma < \hat{\sigma}(\tau)$), there exists an interval $(\underline{\sigma}(\tau), \overline{\sigma}(\tau))$ such that the growth rate goes up for $\underline{\sigma}(\tau) < \sigma < \overline{\sigma}(\tau)$.*
- *When the BGP is initially in or moves to the npm regime ($\sigma > \hat{\sigma}(\tau)$), the growth rate is enhanced and is higher than in the pm regime for $\sigma < \frac{1}{1+\gamma_2\mu}$.*

Proof. See Appendix 2.6.5 ■

Considering a tighter tax, an economy where agents initially invest in private maintenance may switch to the other regime. When the BGP remains in the regime with private maintenance ($\sigma < \hat{\sigma}(\tau)$), an increase in the tax favors both human capital and

[29] Note that examining the impact of environmental awareness component on growth, we obtain that the stronger environmental concerns, the lower the growth rate, as in Prieur & Bréchet (2013). In their paper, a raise in environmental awareness always reduces physical capital accumulation. Here, γ_1 affects growth trough an additional channel as the environment improves education. Nevertheless, the negative direct impact of environmental awareness on education spending more than offsets the positive effect through the improvement of the environment. The proof is available upon request.

environmental quality if the allocation between public spending σ is intermediary. The reason is that extreme allocation makes one private spending too expensive relatively to the other, which leads agents to neglect one of the two actions driving growth. When σ is too low, policy favors mainly education spending. Despite the improvement in environmental consciousness it entails, the increase in the tax makes the private maintenance too expensive, such that the environment deteriorates, and so does the growth rate. Conversely, when σ is too high, the tax revenue contributes mostly to public maintenance. Even if the private investment in environment diminishes in favor of education spending, education cost is too high, which weakens human capital accumulation. Therefore, authorities can increase growth by supporting both education and maintenance. Note that the two thresholds $\underline{\sigma}(\tau)$ and $\overline{\sigma}(\tau)$ increase with the parameters of green preferences β and η. It follows that the higher is environmental awareness, the larger should be the public environmental support to enhance growth.

When households do not invest in private maintenance in the long run or when they stop investing in it following the government intervention ($\sigma > \hat{\sigma}(\tau)$), a tighter tax leads to the highest growth rate as long as it is accompanied by a sufficient support for human capital ($\sigma < 1/(1+\gamma_2\mu)$). The intuition is the following. On the one hand, in the *npm* regime, maintenance is entirely publicly funded despite the willingness of agent to contribute privatively to pollution abatement. Therefore, the environmental quality is sufficiently good. On the other hand, when the government allocates also a high enough share of its budget to education, the negative effect of the tax on available income is more than offset by the positive effect through the education subsidy. In this way, human capital accumulation and the environment are enhanced. Note that when $\sigma > 1/(1+\gamma_2\mu)$, a tighter tax is growth-reducing when maintenance is initially entirely public. This result may also be observed when there is a regime switch, particularly if the increase in τ moving the BGP to the regime without private maintenance is important. In this case, the negative income effect exceeds the positive impact of the education subsidy and hence human capital accumulation deteriorates.

Our results contribute to the literature looking at the effects of policy on sustainable development. As in Ono (2003), environmental taxation exerts competing effects on the long-term economic growth. However, while he observes a positive impact of pollution taxation on growth only for intermediary level of the tax rate, we emphasize that a tighter policy is growth-enhancing as long as the tax revenue is well allocated.

The relationship that we observe between the tax and long-term growth is also tied to results obtained in a recent branch of this literature that considers the role of human capital. On the one hand, some contributions focus on the effect of an environmental policy. In a model with an R&D sector reducing pollution, Grimaud & Tournemaine (2007) find that a higher environmental tax decreases the price of education relatively to the polluting good, such that a tighter tax always promotes growth. This positive effect of taxation is also present in Pautrel (2014) for finite lifetime when abatement sector is more human capital intensive than final output sector. On the other hand, Prieur & Bréchet (2013) deal with the link between human capital and the environment, focusing on the effect of education policy. They obtain that public education can favor human capital accumulation and environmental quality, only when the associated tax is low enough.

We differ from these papers by pointing out the role of policy mix. Even for a high tax rate, we emphasize that the recycling of the tax can lead to a win-win situation, in terms of environmental quality improvement and economic benefit. However, this result is guaranteed only if the government invests in both education and environmental supports. More specifically, despite the positive effect of environmental quality on education, a policy focusing on public maintenance may reduce human capital and growth. Reversely, even if human capital contributes to individuals' environmental awareness, an education policy alone may not be sufficient to enhance the environment, and hence to favor a sustainable growth.

2.4.3 How the government policy can improve the short- and long-term situations?

We emphasize previously the role the government can play in avoiding intergenerational inequalities in the short run, and in enhancing economic and environmental growth in the long run. In this section, we examine how a tighter tax can generate both short- and long-term benefits. For that we consider the properties of the function $\hat{\sigma}(\tau)$, that defines the regimes with and without private maintenance, with the properties of $\sigma_{Min}(\tau)$ and $\sigma_{Max}(\tau)$, that determine the possible policy schemes compatible with sustainable development (see Assumption 1). We summarize the results of Propositions 6 and 7 in Figure 2.2, which depicts the implications of a tighter tax for a given σ.[30] Fourth areas are distinguished.

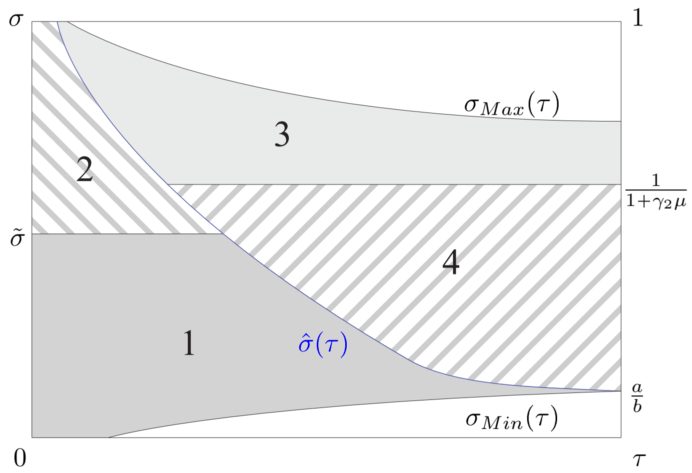


Figure 2.2: Short- and long-term implications of a tighter tax at σ given, when $\frac{a}{b} < \frac{1}{1+\gamma_2\mu}$

In areas 1 and 2, the BGP equilibrium is in the regime with private maintenance. Focusing on the short run, a tighter tax makes the occurrence of oscillations less likely when $\sigma < \tilde{\sigma}$ (area 1), while the opposite holds when $\sigma > \tilde{\sigma}$ (area 2). In these areas,

[30] From Proposition 7, we deduce that a growth enhancing policy exists in the regime *npm* if and only if $\frac{a}{b} < \frac{1}{1+\gamma_2\mu}$, where the ratio $\frac{a}{b}$ represents the minimum level of the threshold $\hat{\sigma}(\tau)$ over which the economy is in the regime without private maintenance.

to improve the long-term growth, an increase in the pollution tax has to be associated with an intermediary level of σ ($\underline{\sigma}(\tau) < \sigma < \overline{\sigma}(\tau)$). Unfortunately, no clear conclusion emerges when comparing these values of σ with the one corresponding to benefit in the short-run.

As long as the tax rate is sufficiently high, the economy can achieve areas 3 and 4, where the BGP is in the regime without private maintenance and hence contributions to the pollution abatement are entirely publicly funded. At this state, the short-term issue vanishes and the economy performs a higher long-term growth rate when the education subsidy is sufficiently high (σ low, area 4). Furthermore, as stressed in Proposition 7, for a given σ, the growth rate is higher in area 4 than in the other regime.[31]

As a result, we identify the most favorable tax scheme as the one where the environmental protection results exclusively in public spending and education support is sufficiently high (area 4). The reasons are twofold: First, even if the efficiency of the public maintenance is the same as the private contribution to the environment, we conclude that the government should take the full responsibility for environmental protection in order to avoid intergenerational inequalities. In this way, households can focus on their children's education and their spendings do no longer respond to possible fluctuations in preferences. This policy seems particularly important as the empirical literature highlights that environmental preferences fluctuate with economic and environmental context (see Dunlap & Scarce , 1991 or Scruggs & Benegal , 2012). Second, in this case, the level of environmental quality is sufficiently high so that agents do not contribute privately to the environment despite the welfare they get from it. Moreover, human capital accumulation is sufficiently supported to achieve both higher environmental and economic growths. Thus, we conclude in favor of an environmental policy mix.

Finally, note that environmental awareness affects the policy scheme to implement.

[31] Note that the design of this policy depends on environmental awareness. For a given σ, the higher green preference parameters, the higher the tax rate required to achieve the area 4 (the curve $\hat{\sigma}(\tau)$ moves to the right).

When green preferences are high, the policy maker has to further orient its policy towards environmental protection, in order to both avoid intergenerational inequalities and improve growth.

2.5 Conclusion

In this paper, we examine the implications of an environmental policy mix on sustainable development, when environmental awareness is endogenously determined by both education and pollution. The government can strengthen its environmental commitment by increasing a tax on pollution and allocate the tax revenue between two categories of environmental expenditure: a public pollution abatement and an education subsidy that aim to develop ecological consciousness. These different instruments affect agents' choices in education and environmental maintenance. If public maintenance is sufficiently high, households may stop to invest privately in maintenance despite the benefits they derive from this investment.

With the present model, we show that the economy can converge to a balanced growth path (BGP), characterized by sustainable growth. When agents' environmental preferences are highly sensitive to human capital and pollution, this convergence may be oscillatory. This is due to the feedback effect of human capital and environmental quality on endogenous environmental awareness, which shapes the trade-off between private choices. Such complex dynamics represents an issue, as it makes the welfare vary across generations and entails intergenerational inequalities.

We reveal that environmental policy may allow to remove these inequalities in two ways: by providing a sufficiently high support in environmental maintenance to remove private contributions or by subsidizing sufficiently education to make the private choices less dependent on green preferences. A tighter tax can also improve the long-term economic and environmental growth rate when the tax revenue is intermediary allocated between the two public expenditures. In this case, human capital accumulation is favored without damaging the environment. Finally, we emphasize that the policy can lead to a win-win situation, by avoiding intergenerational inequalities and improving growth of both human capital and environmental quality. More precisely, the most favorable policy scheme corresponds to an intermediary allocation of tax revenue between public environmental maintenance and education. Thus, we conclude in favor of a policy mix that combines usual environmental instruments with other levers aiming to directly modify environmental behaviors.

2.6 Appendix

2.6.1 Equilibrium

First Order Conditions

The maximization of the consumer program (2.6) leads to the following first order conditions on education expenditure and on environmental maintenance:

$$\frac{\partial U}{\partial e_t} = 0 \Leftrightarrow \frac{1-\theta_t^e}{c_t} = \frac{\gamma_2 \mu}{e_t} \tag{2.19}$$

$$\frac{\partial U}{\partial m_t} \leqslant 0 \Leftrightarrow \frac{1}{c_t} \geqslant \frac{\gamma_{1t}(\varepsilon_1 + \varepsilon_2 b)}{\varepsilon_1 m_t + \varepsilon_2 Q_{t+1}} \tag{2.20}$$

From equations (2.3), (2.5) and the first order conditions (2.19) and (2.20), we deduce the optimal choices in terms of education and maintenance in two regimes: pm (where

$m_t > 0$) and *npm* (where $m_t = 0$).

$$e_t = \begin{cases} \left(\frac{\gamma_2\mu}{1-\theta_t^e}\right)\left(\frac{(\varepsilon_1+\varepsilon_2 b)w_t h_t+\varepsilon_2\left[(1-\alpha)Q_t-aY_t+b(M_t+NG_t^m)\right]}{(1+\gamma_{1t}+\gamma_2\mu)(\varepsilon_1+\varepsilon_2 b)}\right) & pm \\ \frac{w_t h_t \gamma_2\mu}{(1+\gamma_2\mu)(1-\theta_t^e)} & npm \end{cases}$$

$$m_t = \begin{cases} \frac{\gamma_{1t}(\varepsilon_1+\varepsilon_2 b)w_t h_t-\varepsilon_2(1+\gamma_2\mu)\left[(1-\alpha)Q_t-aANh_t+b(M_t+NG_t^m)\right]}{(1+\gamma_{1t}+\gamma_2\mu)(\varepsilon_1+\varepsilon_2 b)} & pm \\ 0 & npm \end{cases}$$

At the symmetric equilibrium, $M_t = m_t(N-1)$, the wage equilibrium is $w_t = A(1-\tau)$, the production function is $Y_t = ANh_t$ and the government budget constraint is given by (2.10). The Nash intertemporal equilibria are thus given by:

$$e_t = \begin{cases} \frac{\gamma_2\mu[c_3 A(1-\tau)h_t+\varepsilon_2((1-\alpha)Q_t+ANh_t(b\sigma\tau-a))]}{\gamma_{1t}c_1+(1+\gamma_2\mu)c_3} + (1-\sigma)\tau Ah_t & pm \\ \frac{Ah_t[\gamma_2\mu(1-\tau)+\tau(1-\sigma)(1+\gamma_2\mu)]}{1+\gamma_2\mu} & npm \end{cases}$$

$$m_t = \begin{cases} \frac{\gamma_{1t}c_1 Ah_t(1-\tau)-\varepsilon_2(1+\gamma_2\mu)[(1-\alpha)Q_t+ANh_t(b\sigma\tau-a)]}{\gamma_{1t}c_1+(1+\gamma_2\mu)c_3} & pm \\ 0 & npm \end{cases}$$

Condition for the regime without private maintenance

Using equation (2.12), we deduce the condition such that the regime without private environmental maintenance occurs:

$$X_t \geqslant \frac{A\left[\gamma_{1t}c_1(1-\tau)-\varepsilon_2 N(1+\gamma_2\mu)(b\sigma\tau-a)\right]}{\varepsilon_2(1+\gamma_2\mu)(1-\alpha)} \tag{2.21}$$

This condition can be written as:

$$\begin{aligned} \mathcal{P}(X_t) \quad \equiv \quad & X_t^2\varepsilon_2(1+\gamma_2\mu)(1-\alpha)+X_t[\varepsilon_2(1+\gamma_2\mu)(1-\alpha+AN(b\sigma\tau-a))-A\eta c_1(1-\tau)] \\ & -A[\beta c_1(1-\tau)-(b\sigma\tau-a)N\varepsilon_2(1+\gamma_2\mu)] \geqslant 0 \end{aligned} \tag{2.22}$$

Given the expression of $\mathcal{P}(X_t)$, the polynomial $\mathcal{P}(X_t) = 0$ admits at most one positive solution. We define Λ as the critical threshold of X_t over which the economy is in the no private maintenance regime, with $\Lambda \equiv \max\{0, sol\{\mathcal{P}(X_t) = 0\}\}$.

- When $\mathcal{P}(X_t) = 0$ does not admit a positive solution, the polynomial is positive or nul $\forall\ X_t \geqslant 0$. In this case, the economy is always in the *npm* regime (i.e $\Lambda = 0$).

- When $\mathcal{P}(X_t) = 0$ admits a positive solution, the economy is in the *npm* regime only when X_t is sufficiently high (i.e $\Lambda > 0$).

As a result, the economy is in the *npm* regime when $X_t \geqslant \Lambda$, with $\Lambda \geqslant 0$.

Growth rates

We define the endogenous growth rate of human capital g_H, and environmental quality g_Q, using equations (2.4), (2.5), (2.13) and (2.12):

$$1+g_{Ht} = \begin{cases} \epsilon\left[\frac{\gamma_2\mu[A(1-\tau)c_3+\varepsilon_2((1-\alpha)X_t+AN(b\sigma\tau-a))]+(1-\sigma)\tau A(\gamma_{1t}c_1+c_3(1+\gamma_2\mu))}{\gamma_{1t}c_1+(1+\gamma_2\mu)c_3}\right]^\mu & pm \\ \epsilon\left[\frac{A[\gamma_2\mu(1-\tau)+\tau(1-\sigma)(1+\gamma_2\mu)]}{1+\gamma_2\mu}\right]^\mu & npm \end{cases} \tag{2.18}$$

In the *npm* regime, human capital growth rate is constant, as education spending does not depend on the environment. The *pm* regime is characterized by a human capital growth rate increasing in the green development index, directly and indirectly though environmental awareness γ_{1t}.

$$1+g_{Qt} = \begin{cases} \frac{(1-\alpha)X_t(\gamma_{1t}c_1+c_2)+AN[\gamma_{1t}\ c_1(1-\tau)b+(\gamma_{1t}c_1+c_2)(b\tau\sigma-a)]}{X_t(\gamma_{1t}c_1+c_3(1+\gamma_2\mu))} & pm \\ 1-\alpha+\frac{AN(b\sigma\tau-a)}{X_t} & npm \end{cases} \tag{2.23}$$

In the case with private maintenance, the green development index X_t has a direct negative impact on the growth rate of environmental quality and an indirect positive effect through environmental awareness γ_{1t}. In the corner solution, g_{Qt} is always negative without public abatement.[32] However, when the government intervenes, the growth of the environmental quality at the corner may be positive for sufficiently high share of policy devoted to public environmental maintenance (σ).

2.6.2 Proof of Proposition 4

Properties of the dynamical equation

From Definitions 3 and 6 and equations (2.14) and (2.16), we emphasize the properties of the dynamical equation characterizing equilibrium paths, $\mathcal{F}(X_t)$, defined on $(0;+\infty)$:

- When $X_t \in (0\ ;\ \Lambda)$ the function is given by equation (2.17 *pm*). We have

$$\mathcal{F}(0) = \frac{AN(\beta\, c_1(1-\tau)b + (\beta c_1 + c_2)(b\tau\sigma - a))}{\epsilon\left[A\gamma_2\mu\,(\,c_3(1-\tau) + \varepsilon_2 N(b\sigma\tau - a)) + (1-\sigma)\tau A(\beta\, c_1 + (1+\gamma_2\mu)c_3)\right]^{\mu}\left[\beta\, c_1 + (1+\gamma_2\mu)c_3\right]^{1-\mu}}$$

  Finally, with equation (2.16), $\lim\limits_{X_t\to\Lambda^-} \mathcal{F}(X_t) = \frac{(1-\alpha)\Lambda + AN(b\sigma\tau - a)}{\epsilon\left[\frac{\gamma_2\mu A(1-\tau)+(1-\sigma)\tau A(1+\gamma_2\mu)}{1+\gamma_2\mu}\right]^{\mu}} \equiv v.$

- When $X_t \in [\Lambda\ ;\ +\infty)$, the function is given by equation (2.17 *npm*). $\mathcal{F}$ is increasing and linear in X, $\mathcal{F}(\Lambda) = v$ and $\lim_{X\to+\infty}\mathcal{F}(X) = +\infty$.

As $\lim\limits_{X_t\to\Lambda} \mathcal{F}(X_t) = \mathcal{F}(\Lambda)$, the function is continue on $(0;+\infty)$.

[32] When $m_t = 0$ and $\sigma = 0$, g_{Qt} is increasing in X_t: an increase in X_t fits in with a human capital decline and hence with a lower pollution.

Existence and Unicity of the Balanced Growth Path

npm solution. A BGP in the *npm* regime is characterized by $\bar{X}_{npm} = \mathcal{F}(\bar{X}_{npm})$. Using (2.17 *npm*), we obtain:

$$\bar{X}_{npm} = \frac{AN(b\tau\sigma - a)}{\epsilon\left[\frac{A[\gamma_2\mu(1-\tau)+(1-\sigma)\tau(1+\gamma_2\mu)]}{1+\gamma_2\mu}\right]^{\mu} - (1-\alpha)} \tag{2.24}$$

To exists $\bar{X}_{npm}$ has to be positive. Following (2.18 *npm*), if the denominator of (2.24) is negative, so does the growth rate in the *npm* regime. Therefore, the case where the denominator and the numerator of (2.24) are negative is meaningless. The existence conditions are thus $\sigma > \frac{a}{b\tau}$ and $\mathcal{A}_1 > 0$ with $\mathcal{A}_1 \equiv \left[\frac{A[\gamma_2\mu(1-\tau)+(1-\sigma)\tau(1+\gamma_2\mu)]}{1+\gamma_2\mu}\right]^{\mu} - (1-\alpha)$. Note that the condition $\mathcal{A}_1 > 0$ implies that $\lim\limits_{X\to+\infty} \frac{\mathcal{F}(X)}{X} < 1$.

Then, we have to check the admissibility of the steady state, i.e. if it effectively belongs to the *npm* region. To do this, we examine the sign of $\mathcal{F}(\Lambda) - \Lambda$. Under condition $\mathcal{A}_1 > 0$ and $\sigma > \frac{a}{b\tau}$, $\bar{X}_{npm}$ is admissible if $\mathcal{F}(\Lambda) \geqslant \Lambda$, which is equivalent to $\bar{X}_{npm} \geqslant \Lambda$.

pm solution. A BGP in the *pm* regime is characterized by $\bar{X}_{pm} = \mathcal{F}(\bar{X}_{pm})$. As we focus on $X > 0$, we determine the solutions $\bar{X}_{pm}$ which satisfy $\mathcal{F}(\bar{X}_{pm})/\bar{X}_{pm} = 1$. Using equations (2.14) and (2.17 *pm.*), it corresponds to the following equation. For the sake of simplicity, subscripts on X are removed.

$$\frac{\epsilon\left[\gamma_2\mu(Ac_3(1-\tau) + \varepsilon_2((1-\alpha)X + AN(b\tau\sigma - a))) + A\tau(1-\sigma)\left(c_1\frac{\beta+\eta X}{1+X} + (1+\gamma_2\mu)c_3\right)\right]^{\mu}}{\left[\frac{\beta+\eta X}{1+X}c_1 + c_3(1+\gamma_2\mu)\right]^{1-\mu}} = (1-\alpha)\left(\frac{\beta+\eta X}{1+X}c_1 + c_2\right) + \frac{AN\left(\frac{\beta+\eta X}{1+X}c_1(b(1-\tau)+b\tau\sigma-a) - c_2(a-b\tau\sigma)\right)}{X}$$

We define $\mathcal{D}_1(X)$ and $\mathcal{D}_2(X)$, respectively the term on the left and on the right hand side. Their properties are:

- $\mathcal{D}_1$ is decreasing and then increasing with X. Moreover, $\mathcal{D}_1(X) > 0$ for all X, $\lim\limits_{X\to 0} \mathcal{D}_1(X) = \mathcal{C} > 0$, with $\mathcal{C}$ a constant and $\lim\limits_{X\to+\infty} \mathcal{D}_1(X) = +\infty$.

- Concerning $\mathcal{D}_2$ we have that if $\mathcal{A}_2 \equiv \beta c_1(b(1-\tau)+b\tau\sigma-a)-c_2(a-b\tau\sigma) > 0$ (resp. < 0), $\lim_{X\to 0} \mathcal{D}_2(X) > 0$ (resp. < 0). Moreover, $\lim_{X\to +\infty} \mathcal{D}_2(X) = (1-\alpha)(\eta c_1+c_2) > 0$.

The condition $\mathcal{A}_2 > 0$ guarantees that the curves $\mathcal{D}_1(X)$ and $\mathcal{D}_2(X)$ cross at least once in the positive area. Thus, a positive solution exists. From equation (2.17 *pm.*) and $\mathcal{A}_2 > 0$, we have $d\mathcal{F}(\bar{X}_{pm})/dX < 1$, hence the positive solution $\bar{X}_{pm}$ is unique.

We check the admissibility of the steady state, i.e. if it effectively belongs to the *pm* region. Under condition $\mathcal{A}_2 > 0$, $\bar{X}_{pm}$ is admissible if $\lim_{X\to\Lambda} \mathcal{F}(X) < \Lambda$, which is equivalent to $\bar{X}_{pm} < \Lambda$. As $\bar{X}_{pm} \leqslant \bar{X}_{npm}$, the condition $\bar{X}_{npm} < \Lambda$ guarantees that $\bar{X}_{pm}$ is admissible.

The case where both $\bar{X}_{pm}$ and $\bar{X}_{npm}$ are admissible is excluded. Indeed, when $\bar{X}_{pm}$ exists (condition $\mathcal{A}_2 > 0$ verified) and is admissible, then $\mathcal{F}(\Lambda) < \Lambda$. But under condition $\mathcal{A}_1 > 0$ the slope of $\mathcal{F}$ in the *npm* regime is lower than one, which means that $\mathcal{F}$ cannot cut the bisector in this regime. Reversely, when X_{npm} exists (conditions $\mathcal{A}_1 > 0$ and $\sigma > \frac{a}{b\tau}$ verified) and is admissible then $\mathcal{F}(\Lambda) \geqslant \Lambda$. Under condition $\mathcal{A}_2 > 0$, this implies that $\mathcal{F}$ does not cut the bisector in the *pm* area.

To sum up, under these conditions it is not possible to have $\bar{X}_{pm} < \Lambda \leqslant \bar{X}_{npm}$, and hence to have cases with multiple steady states: when $\bar{X}_{npm} < \Lambda$, the BGP is in the regime *pm*, while when $\bar{X}_{npm} \geqslant \Lambda$, the BGP is in the regime *npm*.

For the rest of the paper, we rewrite the conditions $\mathcal{A}_1, \mathcal{A}_2 > 0$, as $\sigma_{Min}(\tau) < \sigma < \sigma_{Max}(\tau)$ with

$$\sigma_{Min}(\tau) \equiv \frac{a(\beta c_1 + c_2) - b\beta c_1(1-\tau)}{b\tau(\beta c_1 + c_2)} \;\; \textit{and} \;\; \sigma_{Max}(\tau) \equiv \frac{A(\gamma_2\mu + \tau) - \epsilon^{-1/\mu}(1+\gamma_2\mu)(1-\alpha)^{1/\mu}}{A\tau(1+\gamma_2\mu)}$$

$\sigma_{Min}(\tau)$ is increasing in τ from $\lim_{\tau\to 0}\sigma_{Min} = -\infty$ to $\lim_{\tau\to 1}\sigma_{Min} = a/b$, while $\sigma_{Max}(\tau)$ is decreasing in τ from $\lim_{\tau\to 0}\sigma_{Max} = +\infty$ to $\lim_{\tau\to 1}\sigma_{Max} = 1 - \frac{1}{\epsilon^{1/\mu}A}$.

Condition for the nature of the BGP. The analysis of admissibility conditions comes down to $\bar{X}_{npm} <$ or $> \Lambda$.

From equation (2.22) in Appendix 2.6.1, $\bar{X}_{npm} \geqslant \Lambda$ is equivalent to $\mathcal{P}(\bar{X}_{npm}) \geqslant 0$. We define $\mathcal{P}(\bar{X}_{npm}) \equiv \mathcal{J}(\tau, \sigma)$, where the function $\mathcal{J}$ is increasing in τ and σ. Under $\mathcal{A}_1 > 0$:

- For $\tau = 0$, $\bar{X}_{npm} < 0$, $\mathcal{J} < 0$ and does no longer depend on σ.

- For $\tau = 1$, we get $\mathcal{J} > 0 \ \ \forall \, \sigma \in [0, 1]$.

We depict a representation of $\mathcal{J}$ at given τ:

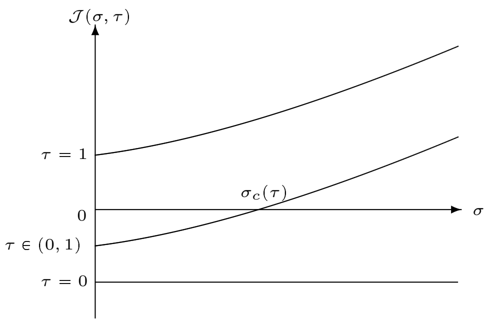


Figure 2.3: Function $\mathcal{J}$ at given τ

We deduce that there exists a $\sigma_c(\tau)$ decreasing in τ such that $\mathcal{J} = 0$, with $\lim\limits_{\tau \to 0} \sigma_c(\tau) = +\infty$ and $\sigma_c(1) < 0$. Thus a minimum level of the tax is required to make the *npm* regime possible. When $\sigma < \sigma_c(\tau)$, we get $\mathcal{P}(\bar{X}_{npm}) < 0$, meaning that the equilibrium is in the *pm* regime. Respectively, when $\sigma \geqslant \sigma_c(\tau)$ we get $\mathcal{P}(\bar{X}_{npm}) \geqslant 0$, and from equations (2.22) and (2.24) we have $\bar{X}_{npm} \geqslant \Lambda$ if and only if $\sigma > \frac{a}{b\tau}$. Thus, the BGP is in the *npm* regime when $\sigma > Max\{\sigma_c(\tau); \frac{a}{b\tau}\} \equiv \hat{\sigma}(\tau)$ and in the *pm* regime when $\sigma < \hat{\sigma}(\tau)$. When $\sigma = \hat{\sigma}(\tau)$, the BGP is in the *npm* regime if $\hat{\sigma}(\tau) = \sigma_c(\tau)$ and in the *pm* regime if $\hat{\sigma}(\tau) = \frac{a}{b\tau}$. Note that $\hat{\sigma}(\tau) > \sigma_{Min}(\tau)$ and $\lim_{\tau \to 1} \hat{\sigma}(\tau) < \lim_{\tau \to 1} \sigma_{Max}(\tau)$. $\square$

2.6.3 Proof of Proposition 5

pm solution. We use the scaling parameter ϵ in order to normalize the steady state $\bar{X}_{pm}$ to one. There is a unique solution ϵ^* such that $\bar{X}_{pm} = 1$ and from equation (2.17 pm), the expression of the normalization constant is given by:

$$\begin{aligned}&\epsilon^*(\bar{X}_{pm}) \equiv \left[(1-\alpha)\ \bar{X}_{pm}\ \left[\bar{\gamma_1} c_1 + c_2\right] + AN(\bar{\gamma_1} c_1 b(1-\tau) + (\bar{\gamma_1} c_1 + c_2)(b\tau\sigma - a))\right] \\ &\left[\gamma_2\mu A\ c_3(1-\tau) + \gamma_2\mu\varepsilon_2\left[(1-\alpha)\bar{X}_{pm} + AN(b\sigma\tau - a)\right] + (1-\sigma)\tau A(\bar{\gamma_1}\ c_1 + (1+\gamma_2\mu)c_3)\right]^{-\mu} \\ &\left[\bar{\gamma_1}\ c_1 + (1+\gamma_2\mu)c_3\right]^{\mu-1}\end{aligned}$$

Then, by differentiating equation (2.17 pm.) and analyzing it around the steady state $\bar{X}_{pm} = 1$ and $\epsilon \equiv \epsilon^*(\bar{X}_{pm})$, we obtain:

$$dX_{t+1} = \frac{((1-\alpha)(\bar{\gamma_1}c_1 + c_2 + \bar{\gamma_1}'c_1) + AN\bar{\gamma_1}'c_1(b(1-\tau) + b\tau\sigma - a))\mathcal{B}_1\mathcal{B}_2 - \mathcal{B}_3\left(\mu\mathcal{B}_2(\gamma_2\mu\varepsilon_2(1-\alpha) + (1-\sigma)A\tau\bar{\gamma_1}'c_1) + (1-\mu)\gamma_1' c_1\mathcal{B}_1\right)}{\mathcal{B}_3\mathcal{B}_1\mathcal{B}_2} dX_t \tag{2.25}$$

with $\bar{\gamma_1} = \frac{\beta+\eta}{2}$, $\bar{\gamma_1}' = (\eta-\beta)/4$, $\mathcal{B}_1 = \gamma_2\mu A\ c_3(1-\tau) + \gamma_2\mu\varepsilon_2\left[(1-\alpha) + AN(b\sigma\tau - a)\right] + (1-\sigma)\tau A(\bar{\gamma_1}\ c_1 + (1+\gamma_2\mu)c_3)$, $\mathcal{B}_2 = \bar{\gamma_1}\ c_1 + c_3(1+\gamma_2\mu)$ and $\mathcal{B}_3 = (1-\alpha)(\bar{\gamma_1}\ c_1 + c_2) + AN(\bar{\gamma_1}c_1 b(1-\tau) + (\bar{\gamma_1}c_1 + c_2)(b\tau\sigma - a))$.

From (2.25), we get $dX_{t+1}/dX_t < 1$. Thus, when $dX_{t+1}/dX_t > 0$, transitional dynamics is monotonous and the BGP equilibrium is locally stable. Using equation (2.25), we have $dX_{t+1}/dX_t > 0$ if and only if:

$$\begin{aligned}&\mathcal{B}_2(1-\alpha)\left[(1-\sigma)\tau A\mathcal{B}_2 + \gamma_2\mu(A\varepsilon_1(1-\tau) + \varepsilon_2(1-\mu))\right](\gamma_1 c_1 + c_2) \\ +\ &\mathcal{B}_2(1-\alpha)A\varepsilon_2 bN(1-\tau)(\gamma_1 c_1(1-\mu) + c_2) \\ +\ &\bar{\gamma_1}'c_1\mathcal{B}_5\left[\gamma_2\mu(1-\alpha + AN(b-a) + bN\tau(\sigma-1))(bN(1+\gamma_2\mu)\varepsilon_2(1-\mu) + \mu\mathcal{B}_2)\right] \\ +\ &\bar{\gamma_1}'c_1\mathcal{B}_5 ANb(1+\gamma_2\mu)(\gamma_2\mu\varepsilon_1(1-\mu) + (1-\sigma)\tau\mathcal{B}_2) > 0\end{aligned}$$

with $\mathcal{B}_4 \equiv 1-\alpha + AN(b(1-\tau) + b\tau\sigma - a)$ and $\mathcal{B}_5 \equiv Ac_3(1-\tau) + \varepsilon_2(1-\alpha + AN(b\tau\sigma - a))$.

Rewriting this expression, we have $dX_{t+1}/dX_t > 0$ if and only if the following polynomial is positive:

$$\mathcal{R}(\beta) \equiv a_1\beta^3 + a_2\beta^2 + a_3\beta + a_4$$

with $a_4 > 0$ and expressions for a_1, a_2 and a_3 given by:

$$a_1 = \frac{c_1^3}{8}(1-\sigma)(1-\alpha)\tau A > 0$$

$$\begin{aligned} a_2 = & \tfrac{c_1^2(1-\alpha)}{4}\left[\gamma_2\mu(1-\mu)\mathcal{B}_5 + (1-\sigma)\tau A[2c_3(1+\gamma_2\mu)+c_2] + \gamma_2\mu^2\varepsilon_1 A(1-\tau)\right] \\ & + \tfrac{c_1^2}{8}\left[3\eta c_1(1-\alpha)(1-\sigma)\tau A - \mathcal{B}_5\left(\gamma_2\mu^2\mathcal{B}_4 + bAN(1+\gamma_2\mu)\tau(1-\sigma)\right)\right] \end{aligned}$$

$$\begin{aligned} a_3 = & \tfrac{c_1^3\eta^2(1-\sigma)(1-\alpha)\tau A}{8} + \tfrac{2\eta c_1^2}{4}(1-\alpha)\left[\gamma_2\mu(1-\mu)\mathcal{B}_5 + (1-\sigma)\tau A[2c_3(1+\gamma_2\mu)+c_2] + \gamma_2\mu^2\varepsilon_1 A(1-\tau)\right] \\ & + \tfrac{c_1(1-\alpha)}{2}\left[3(1-\sigma)\tau Ac_2c_3(1+\gamma_2\mu) + (1-\mu)\gamma_2\mu\mathcal{B}_5(c_3(1+\gamma_2\mu)+c_2) + 2\gamma_2\mu^2 A(1-\tau)\varepsilon_1 c_3(1+\gamma_2\mu)\right] \\ & - \tfrac{c_1\mathcal{B}_5}{4}\left[\gamma_2\mu^2 c_3(1+\gamma_2\mu)\mathcal{B}_4 + bN(1+\gamma_2\mu)(\gamma_2\mu(1-\mu)\mathcal{B}_5 + (1-\sigma)\tau Ac_3(1+\gamma_2\mu))\right] \end{aligned}$$

We have $\mathcal{R}(1)$ which is a polynomial of degree three in N. When $N = 0$, we have $\mathcal{R}(1) > 0$, while when N tends to ∞, $\mathcal{R}(1) < 0$. As N^3 intervenes positively in $\mathcal{R}(1)$, there exists a critical threshold $\bar{N}$ over which the dynamics is oscillatory for $\beta = 1$. Given that $a_1 > 0$ and $a_4 > 0$, we can conclude that for $N > \bar{N}$ there exists a $\tilde{\beta} \in (0, 1]$ over which the dynamics is oscillatory.

We examine the stability of the equilibrium when the dynamics is oscillatory. From equation (2.25), we have $dX_{t+1}/dX_t > -1$ if and only if:

$$\begin{aligned} & [(1-\alpha)(\bar{\gamma}_1 c_1 + c_2 + \bar{\gamma}_1' c_1) + AN\bar{\gamma}_1' c_1(b(1-\tau) + b\tau\sigma - a)]\mathcal{B}_1\mathcal{B}_2 + \mathcal{B}_1\mathcal{B}_2\mathcal{B}_3 \\ - & [(1-\mu)c_1\bar{\gamma}_1'\mathcal{B}_1 + \mathcal{B}_2\mu\left(\gamma_2\mu\varepsilon_2(1-\alpha) + (1-\sigma)A\tau\bar{\gamma}_1' c_1\right)]\mathcal{B}_3 > 0 \end{aligned}$$

Replacing expressions $\mathcal{B}_1$, $\mathcal{B}_1$ and $\mathcal{B}_3$, we finally obtain:

$$
\begin{aligned}
& c_3(1+\gamma_2\mu)c_2(1-\alpha)(\mathcal{B}_6+\varepsilon_2 bN\mu)+\gamma_2\mu(\bar{\gamma_1}c_1)^2(\mathcal{B}_6(1-\alpha)+\mathcal{B}_5\mathcal{B}_4)\\
+ \;& \bar{\gamma_1}c_1(1+\gamma_2\mu)[(1-\alpha)\varepsilon_1(\mathcal{B}_6+\varepsilon_2 bN\mu)+\gamma_2\mu\varepsilon_1(1-\alpha+AN(b\tau\sigma-a))+c_3(\mathcal{B}_4+\mathcal{B}_6)]\\
+ \;& \gamma_2\mu\bar{\gamma_1}'c_1(1+\gamma_2\mu)(\mathcal{B}_4c_3-(1-\mu)\varepsilon_1(1-\alpha+AN(b\tau\sigma-a)))\\
+ \;& \gamma_2\mu^2\bar{\gamma_1}'\bar{\gamma_1}c_1^2\mathcal{B}_5\mathcal{B}_4+\mathcal{B}_5c_3(1+\gamma_2\mu)c_2(1-\alpha+AN(b\tau\sigma-a))\\
+ \;& (1-\sigma)\tau A(\bar{\gamma_1}c_1+c_3(1+\gamma_2\mu))\gamma_1'c_1bN(1+\gamma_2\mu)\mathcal{B}_5\\
+ \;& (1-\sigma)\tau A(\bar{\gamma_1}c_1+c_3(1+\gamma_2\mu))^2[\bar{\gamma_1}c_1\mathcal{B}_4+c_2(1-\alpha+AN(b\tau\sigma-a))+(1-\alpha)(\bar{\gamma_1}c_1+c_2)]
\end{aligned}
$$

with $\mathcal{B}_6 = c_2 + \varepsilon_2 bN(1+\gamma_2\mu) > 0$.

As $-\bar{\gamma_1}' < \bar{\gamma_1}$ and $c_3\mathcal{B}_4 > bN\mathcal{B}_5$, we easily see that this term is always positive. The BGP equilibrium is always locally stable.

npm solution. The *npm* BGP is obtain from (2.17 *npm*) and given in Appendix 2.6.2. We differentiate equation (2.17 *npm*) and obtain:

$$\frac{d\mathcal{F}(X_t)}{dX_t} = \frac{(1-\alpha)}{\epsilon\left[\frac{A[\gamma_2\mu(1-\tau)+(1-\sigma)\tau(1+\gamma_2\mu)]}{1+\gamma_2\mu}\right]^{\mu}}$$

Under Assumption 1, the slope of $\mathcal{F}(X_t)$ in the *npm* regime is always positive and lower than one, the *npm* BGP is thus monotonously stable.

□

2.6.4 Proof of Proposition 6

The condition to observe oscillatory cases given in Appendix 2.6.3 (i.e $N > \bar{N}$) depends on policy instruments. Moreover, by examining the terms a_2 and a_3 given Appendix 2.6.3, we conclude that if a_2 is positive, a_3 is positive as well. A necessary condition is thus required to have $N > \bar{N}$: the term a_2 has to be negative. An analysis of the impact of the policy instruments on the polynomial $\mathcal{R}(\beta)$ is not analytically tractable, but the analysis of sgn $\left\{\frac{\partial a_2}{\partial \tau}\right\}$ gives us interesting intuitions. Using the expression of a_2

given in Appendix 2.6.3 we obtain:

$$\text{sgn}\left\{\frac{\partial a_2}{\partial \tau}\right\} = -(1-\sigma)bAN(1+\gamma_2\mu(1-\mu))(\mathcal{S}_2 - \tau A\varepsilon_2 bN(1-\sigma))(\tau(1-\sigma)\mathcal{S}_3 + (1-\tau)\gamma_2\mu A\varepsilon_1)$$
$$+(1-\sigma)(b\tau(1-\sigma)AN(1+\gamma_2\mu(1-\mu)) + \mathcal{S}_1)(\varepsilon_2 ANb\mathcal{S}_4 + \mathcal{S}_3\mathcal{S}_2) + 3(1-\sigma)\eta c_1 A\mathcal{S}_4$$
$$-A\varepsilon_1\mu^3(1-\alpha+AN(b-a))(\mathcal{S}_1 + b\tau(1-\sigma)AN(1+\gamma_2\mu(1-\mu)))$$

with $\mathcal{S}_1 = \mu^2\gamma_2(1-\alpha+AN(b-a))$, $\mathcal{S}_2 = A(1-\tau)\varepsilon_1 + \varepsilon_2(AN(b-a)+1-\alpha)$, $\mathcal{S}_3 = A(3\varepsilon_1(1+\gamma_2\mu) + 2\varepsilon_2 bN + \gamma_2\mu\varepsilon_2 bN(1+\mu))$ and $\mathcal{S}_4 = \gamma_2\mu(\varepsilon_2(1-\mu)(1-\alpha+AN(b-a)) + A\varepsilon_1)$

We can define $\text{sgn}\left\{\frac{\partial a_2}{\partial \tau}\right\}$ as a polynomial of degree three in σ, with $\frac{\partial a_2}{\partial \tau} < 0$ when $\sigma = 1$ and $\frac{\partial a_2}{\partial \tau} > 0$ when $\sigma = 0$. Since $\text{sgn}\left\{\frac{\partial a_2}{\partial \tau}\right\}$ is decreasing in σ for $\sigma \in [0,1]$, there exists a critical value $\tilde{\sigma} \in (0,1)$ such that: for $0 < \sigma < \tilde{\sigma}$, $\frac{\partial a_2}{\partial \tau} > 0$ and for $\tilde{\sigma} < \sigma < 1$, $\frac{\partial a_2}{\partial \tau} < 0$. Moreover, from Assumption 1, $\lim_{\tau\to 0}\sigma_{Min}(\tau) < \tilde{\sigma} < \lim_{\tau\to 1}\sigma_{Max}(\tau)$. When σ is sufficiently low, a tighter tax tightens the condition to observe oscillatory cases, while when σ is high enough the condition to observe oscillatory dynamics may be relaxed.

□

2.6.5 Proof of Proposition 7

We examine the impact of taxation on the growth rate along the BGP.

pm solution. Using equation (2.18 *pm*) with $X_t = \bar{X}_{pm}$ we have:

$$\begin{aligned}\text{sgn}\left(\frac{\partial g_{pm}}{\partial \tau}\right) &= \mathcal{V}_2\left((1-\sigma)(\bar{\gamma}_1 c_1 + c_3) - \sigma\gamma_2\mu\varepsilon_1 + \gamma_2\mu\varepsilon_2(1-\alpha)\frac{\partial \bar{X}_{pm}}{\partial \tau}\right) \\ &+ \frac{c_1(\beta-\eta)}{(1+\bar{X}_{pm})^2}\frac{\partial \bar{X}_{pm}}{\partial \tau}\gamma_2\mu\left(\mathcal{V}_1 - \tau(1-\sigma)A\mathcal{V}_2\right)\end{aligned}$$

with $\mathcal{V}_1 = \gamma_2\mu Ac_3(1-\tau) + \gamma_2\mu\varepsilon_2\left[(1-\alpha)\bar{X}_{pm} + AN(b\sigma\tau - a)\right] + (1-\sigma)\tau A(\bar{\gamma}_1 c_1 + (1+\gamma_2\mu)c_3)$ and

$\mathcal{V}_2 = \bar{\gamma}_1 c_1 + (1+\gamma_2\mu)c_3$. From the implicit function theorem and equation (2.17), we have:

$$\frac{\partial \bar{X}_{pm}}{\partial \tau} = \Big(\mathcal{V}_2\bar{X}_{pm}A\left[(\bar{\gamma}_1 c_1(\sigma-1)+\sigma c_2)\mathcal{V}_1 N - \mu\mathcal{V}_3(-\sigma\varepsilon_1\gamma_2\mu + (1-\sigma)(\bar{\gamma}_1 c_1 + c_3))\right]\Big)$$
$$\Big[\frac{c_1\bar{X}_{pm}(\beta-\eta)}{(1+\bar{X}_{pm})^2}\big(\mathcal{V}_1\mathcal{V}_2(\bar{X}_{pm}(1-\alpha)+AN(b(1-\tau)+b\tau\sigma-a))$$
$$-\mu\mathcal{V}_2\mathcal{V}_3(1-\sigma)\tau A + (1-\mu)\mathcal{V}_1\mathcal{V}_3\big) + \mu\mathcal{V}_2\mathcal{V}_3\bar{X}_{pm}\gamma_2\mu\varepsilon_2(1-\alpha) + AN\mathcal{V}_1\mathcal{V}_2\mathcal{V}_4\Big]^{-1}$$

with $\mathcal{V}_3 = (1-\alpha)\bar{X}_{pm}\left[\bar{\gamma}_1 c_1 + c_2\right] + AN\left[\bar{\gamma}_1 c_1 b(1-\tau) + (\bar{\gamma}_1 c_1 + c_2)(b\tau\sigma - a)\right]$ and $\mathcal{V}_4 = c_2(b\tau\sigma - a) + \bar{\gamma}_1 c_1 b(1-\tau(1-\sigma))$

Thus, substituting $\frac{\partial \bar{X}_{pm}}{\partial \tau}$ in sgn $\left(\frac{\partial g_{pm}}{\partial \tau}\right)$, we finally obtain:

$$\text{sgn}\left(\frac{\partial g_{pm}}{\partial \tau}\right) = \left(\gamma_2\mu\varepsilon_2(1-\alpha)\mathcal{V}_2\bar{X}_{pm}AN + \frac{c_1\bar{X}_{pm}AN(\beta-\eta)}{(1+\bar{X}_{pm})^2}\left[\mathcal{V}_1 - \tau(1-\sigma)A\mathcal{V}_2\right]\right)(\bar{\gamma}_1 c_1(\sigma-1)+\sigma c_2)$$
$$+\left(\frac{c_1\bar{X}_{pm}(\beta-\eta)}{(1+\bar{X}_{pm})^2}\left[\mathcal{V}_2(\bar{X}_{pm}(1-\alpha)+AN(b(1-\tau)+b\tau\sigma-a))+\mathcal{V}_3\right]+\mathcal{V}_2\mathcal{V}_4 AN\right)(-\sigma\varepsilon_1\gamma_2\mu+(1-\sigma)(\bar{\gamma}_1 c_1 + c_3))\mathcal{V}_1$$

Under Assumption 1, policy improves the BGP growth rate when the following sufficient condition is satisfied:

$$f_1(\sigma) < \sigma < f_2(\sigma)$$

with $f_1(\sigma) \equiv \frac{\bar{\gamma}_1 c_1}{\bar{\gamma}_1 c_1 + c_2} < 1$ and $f_2(\sigma) \equiv \frac{\bar{\gamma}_1 c_1 + c_3}{\bar{\gamma}_1 c_1 + c_2 + \gamma_2\mu\varepsilon_1} < 1$. These two functions are increasing in $\bar{\gamma}_1$, and as $\frac{\partial \bar{\gamma}_1}{\partial \bar{X}_{pm}} < 0$ and $\frac{\partial \bar{X}_{pm}}{\partial \sigma} > 0$, they are decreasing in σ. As a result, there exists a unique range of value $[\underline{\sigma}(\tau);\overline{\sigma}(\tau)]$ which satisfies this condition. Moreover, under Assumption 1, $\lim_{\tau\to 0}\sigma_{Min}(\tau) < \underline{\sigma}(\tau) < \overline{\sigma}(\tau) < \lim_{\tau\to 1}\sigma_{Max}(\tau)$.

npm solution. We use equation (2.18 *npm*) with $X_t = \bar{X}_{npm}$ and deduce:

$$\text{sgn}\left(\frac{\partial g_c}{\partial \tau}\right) = 1 - \sigma(1+\gamma_2\mu)$$

A tighter tax is growth promoting as long as $\hat{\sigma}(\tau) < \sigma < 1/(1+\gamma_2\mu)$.

Regime switch. We consider the case where an increase in τ leads the economy from a *pm* regime to a *npm* regime. The opposite switch cannot be observed as $\hat{\sigma}(\tau)$ is decreasing in τ. For a given σ, we compare equations (2.18 *npm*) and (2.18 *pm*), by considering a higher tax rate in the *npm* regime (τ_N) than in the *pm* one (τ_P). The growth rate in the *pm* regime is higher than in the *npm* if and only if:

$$\begin{aligned}&\gamma_2\mu(1+\gamma_2\mu)\left(c_3 A(\tau_N-\tau_P)+\varepsilon_2((1-\alpha)\bar{X}_{pm}+AN(\sigma b\tau_P-a))\right)\\&-(1-\sigma)A(\gamma_1 c_1+(1+\gamma_2\mu)c_3)(\tau_N-\tau_P)-A\gamma_2\mu(1-\tau_N)\gamma_1 c_1>0\end{aligned}$$

This expression is increasing in σ and from (2.16) is never satisfied when $\sigma = 1/(1+\gamma_2\mu)$. And according to Appendix 2.6.2, the *npm* regime exists only if $\frac{a}{b} < \sigma$. Thus, for a given $\sigma \in (a/b\,; 1/(1+\gamma_2\mu))$, the growth rate in the *npm* regime is higher than in the *pm* one. Moreover, under Assumption 1, $\sigma_{Min}(\tau) < 1/(1+\gamma_2\mu) < \sigma_{Max}(\tau)$.

□

2.6.6 Discussion about social welfare

In this section, we provide insights about the externalities existing in the model which justify the intervention of a policy maker. There are several of them in terms of education and maintenance choices.

Concerning education, there are several intergenerational externalities: When choosing education for her child, agents ignore that, human capital being a stock, their choices affect also the stock of knowledge of future generations through inherited human capital. In addition, they do not consider that the investment in education improves the environmental awareness of their descendants, since environmental preferences are endogenously determined by individual's human capital. Finally, they do not take into account the effect of this choice on pollution through the production process, which may leads to an over-accumulation of human capital. Therefore, these opposite externalities can lead education to have a social return lower or higher than its private returns.

Concerning maintenance choices, there are also several externalities. First, an externality comes from the Cournot-Nash decision process which is inefficient and leads to under-contribution of private agents to environmental maintenance. A second externality is intergenerational and due to the fact that environmental quality is a stock. Individuals do not take into account the effect of their contribution to pollution abatement on future generations. This externality is twofold since agent values both the current and the future environmental quality. Finally, there is an other intergenerational externality due to the fact that an improvement of environmental quality tends to reduce agent's efforts for environmental protection (green preferences goes down).

Given the number and the different directions of externalities, we are not able to make a comparison between the optimal solution and the competitive one analytically, such that it is not possible to determine the optimal policy scheme, even along the balanced growth path where X and γ_1 are constant. However, we can underline that a mix of instruments would be required to decentralize the optimum. An education subsidy would compensate the under-accumulation of human capital, while a public maintenance would compensate the under-maintenance.

CHAPTER 3

Environmental Policy and Inequality: a Matter of Life and Death

3.1 Introduction

While the average life expectancy has globally increased during the last decades, health inequalities have not only persisted but widened sharply. For example, Singh & Siahpush (2006) highlight that the absolute difference in life expectancy between less-deprived groups and more deprived groups has risen by over 60% between 1980 and 2000 in the United States. Such disparities in terms of life expectancy represent a worldwide phenomenon. OECD (2013) reports that on average the gap in expected years of life between men with the highest level and the lowest level of education was of 7.8 years in 2010.[1] In Europe, the excess risk of dying among middle-aged adults in the lowest socioeconomic groups ranges from 25% to 150% (Mackenbach , 2006). The extent of this problem has crucial impacts on our societies, not only because health inequalities are unfair and costly in terms of wellbeing, but also because it has important economic consequences, through increased health and social costs, lowered productivity, discouraged investments in education and savings, etc.. Therefore, addressing health disparities has become a major political issue and many governments explicitly aimed to eliminate such

[1] More precisely, this value corresponds to the average expected years of life remaining at age 30 among 14 OECD countries.

inequalities, so far without success (see e.g. reports of the U.S. Department of Health and Human Services , 2000 or of the U.K. Department of Health , 2003).

In this paper, we aim to study if an environmental policy can represent a useful tool for removing existing health inequalities. The reason why we are interested in the role of the environment in this issue is twofold. First, regarding determinants of life expectancy, there is considerable evidence that pollution has a positive and significant effect on mortality (see e.g. Bell & Davis , 2001 ; Pope *et al.* , 2002 ; Bell *et al.* , 2004 or Evans & Smith , 2005). In particular, air pollution was found to be responsible for around 7 million of premature deaths in 2012, representing 1 in 8 of total global deaths (WHO , 2014).[2] At an aggregate level, Pimentel *et al.* (1998) even show that 40% of the world deaths each year can be attributed to direct and indirect effects of environmental degradation.

Second, a key characteristic of the relationship between the environment and health seems to be the unequal repartition of the health effects of pollution across population. In this sense, Stiglitz argues that "environmental degradation is everyone's problem but it is especially a problem for the poor, who are less able to respond effectively".[3] This observation is broadly supported by empirical studies, which provide evidence of an increased susceptibility to mortality from pollution of disadvantaged populations in terms of education and income (see e.g. Cifuentes *et al.* , 1999 ; Health Effects Institute , 2000 ; Pope *et al.* , 2002 ; O'Neill *et al.* , 2003 ; Laurent *et al.* , 2007 or Cakmak *et al.* , 2011). For the United States, Zeka *et al.* (2006) reveal that the mortality risk associated with particulate matter PM_{10} for low educated individuals is more than twice the size of the risk for individuals with high education.[4]

Among the socioeconomic indicators, education is found to have the strongest effect

[2] Specifically, air pollution plays an important role in the development of respiratory and heart diseases (asthma, cancer, stroke...) which can be fatal.

[3] See his Resources 2020 lecture given in October 2012, http://www.rff.org/resources2020.

[4] This study deals with US population in twenty cities between 1989 and 2000. Low education corresponds to less than 8 years of schooling, while high education refers to 13 years or more.

on mortality, and to persist after controlling for other determinants such as income and employment (see among others Elo & Preston , 1996 ; Lleras-Muney , 2005 ; Cutler & Lleras-Muney , 2010 or Miech *et al.* , 2011). For example, in 2009, the death rate of individuals with low education (less than high school diploma) was 2.7 times higher than for those with high education (with some college degree) in the United States.[5] This relationship appears to be due to several effects: more educated individuals are more likely to live and work in better socio-economic conditions, but also to enjoy better information leading to healthier behaviors and to have a better access to healthcare (see Kenkel , 1991 or Laurent *et al.* , 2007). Cutler & Lleras-Muney (2010) find that the education gradient, i.e. differences in health behaviors by education, is explained at 30% by income, health insurance and family background, at 30% by knowledge and cognitive ability and at 10% by social networks.

Therefore, empirical evidence suggests that life expectancy depends on pollution but also on human capital, which is unequally distributed across population. The resulting disparities in health effects of pollution observed among households, then raise the question of the role that could play an environmental policy in reducing inequalities in the economy. That is why we attempt to address the issue of health inequalities with such a policy tool in this paper. More precisely, in a framework where life expectancy is endogenously determined by the level of pollution and the individual human capital, we aim to analyze the implications of an environmental tax, whose revenue is used for pollution abatement, on inequality and growth.

So far, from a theoretical point of view, there has been an increasing interest for life expectancy and its interaction with human capital and/or pollution but very little consideration has been given to health inequalities. Indeed, the positive effect of human capital on life expectancy has been taken into account in few contributions as Blackburn

[5] See the Supplemental tables of the report “Deaths: Final Data for 2009" on the National Center for Health Statistics website.

& Cipriani (2002), Castello-Climent & Domenech (2008) or Mariani *et al.* (2010), which identify the risk of an underdevelopment trap where education and longevity are low. In the same way, the effect of pollution on health through the mortality channel has been studied in several papers, without consensus on the effect of an environmental policy on the economy and in particular on growth (see e.g. Pautrel , 2008 ; Jouvet *et al.* , 2010 ; Mariani *et al.* , 2010 ; Palivos & Varvarigos , 2010 ; Varvarigos , 2011 ; Varvarigos & Zakaria , 2013b or Raffin & Seegmuller , 2014).[6] However, despite the widening health disparities, none of the cited papers consider the uneven distribution of health. A notable exception is Castello-Climent & Domenech (2008), who are interested in the relationship between inequality and a longevity index determined by parents' human capital. Focusing on a form of human capital depending only on an investment in time, they find that the presence of a trap, in which poor individuals have high mortality rate, is possible. Here, we extent this analysis in order to take into account a more complete relationship between health and inequalities. For that, we consider additional determinants of the stock of human capital, i.e. the intergenerational transmission and the quality of the school system (average human capital of society) as in Tamura (1991) or de la Croix & Doepke (2003), and we take into account the effects of pollution on health. Moreover, in this framework, we study the role of an environmental policy on inequalities and endogenous growth.

More closely related to our paper, Aloi & Tournemaine (2013) and Schaefer (2014) take into account the relationship between health, pollution and inequalities. In their models, households are heterogeneous in terms of human capital and suffer from different health effects of pollution. On one hand, Aloi & Tournemaine (2013) formalize a model where pollution has a direct effect on human capital accumulation and find that a tighter environmental policy always reduces income inequality, as lower-skilled are assumed to

[6]Other contributions have also considered the morbidity aspect by considering the negative effect of pollution on productivity or on human capital accumulation (van Ewijk & van Wijnbergen , 1995 ; Aloi & Tournemaine , 2011 or Raffin , 2012).

be more affected by pollution, and it can also improve growth, if the tax is not too high. On the other hand, in a framework where the health effects of pollution and human capital go through child mortality, Schaefer (2014) obtains that pollution impose an increase in inequalities and a decline of growth, through the drop in the willingness of parents to invest in education. Here, we first depart from these contributions by looking at a different health mechanism, i.e. adult mortality. Moreover, in accordance with empirical evidence mentioned above, we endogenize disparities in the effect of pollution on health, in the sense that in our model the vulnerability of an agent to pollution depends on her level of human capital and hence evolves with it.

More precisely, we formalize an overlapping generations model, where agents can live up to three periods depending on their survival probability when old. Their longevity is endogenously determined by their human capital and the level of pollution, in accordance with empirical evidence. Pollution is represented as a flow due to aggregate production, while human capital is the source of endogenous growth but also of the heterogeneity among households.

We obtain that there may exist multiple balanced growth paths. There is always a long-term equilibrium without inequality, while one or several long-term equilibria with inequalities may also occur. Through a numerical illustration, we draw two cases. First, the balanced growth path without inequality is the only one but is a saddle point, so that it delimits a huge inequality trap. Second, this long-term state without inequality is stable and coexists with a long-term equilibrium with inequalities delimiting an inequality trap with a smaller size than the first case. Therefore, we obtain that a trap where inequalities persistently grow always exist, but its size depends on the parameters of the model. Human capital is accumulated through intergenerational transmission, investment in education done by altruistic parents and the educational system (represented by the average human capital). The two former elements perpetuate inequalities, whereas the latter favors human capital convergence. As we consider that longevity depends on pollution and on the individual's human capital, it follows that preferences for the future and the return on investment in education evolve according to these variables. When pollution or inequalities are high in the economy, lower-skilled agents die sooner, thus they benefit only for a short period of time from their investment, and they have a lower return to educate their children. It follows that the gap in human capital increases for the future generation.

When initial levels of inequalities and/or pollution are too large, the economy is stuck in the trap where disparities worsen across time, but when these levels are sufficiently low, the economy can converge in the long run to an equilibrium where inequalities vanish among households. We find also that inequalities in terms of human capital and hence of health have a cost in terms of growth and development in addition to the human cost, as the long-term growth is always lower when there are inequalities. Therefore, the levels of inequalities and pollution are crucial to determine the long-term situation if the economy. Moreover, the fact that if the pollution intensity is high, the economy is likely to be stuck in an inequality trap raises questions about the possible redistributive power of an environmental policy and about its effect on growth.

We analyze if an environmental policy, that reduces pollution, can be sufficient to improve growth and to reduce or eliminate disparities in the economy. We emphasize that a tighter tax on pollution associated with an investment in environmental protection reduces the size of the inequality trap and thus can allow the economy to escape from the trap. It comes from the fact that lower-skilled households are more vulnerable to the negative health effects of pollution than higher-skilled agents. Therefore, the improvement in environmental quality increases more the return on investment in education of lower-skilled than the one of higher-skilled parents. However, a tighter tax on pollution may be insufficient to get out of the trap, especially for moderate tax rate. If the level of inequalities and/or pollution are too high, the level of the tax on pollution required to overcome existent disparities may be very high. Consequently, such environmental policy is an efficient tool to reduce inequalities in the short run and remove them entirely in the long-run but the government should implement it as soon as possible, before the gap among agents is too wide. Moreover, we show that a tighter environmental policy enhances the long-term growth rate of the economy, through the positive effect of the decrease in pollution on life expectancy and the resulting increase in preferences for education, which enhances human capital accumulation.

The paper is organized as follows. In Section 3.2, we set up the theoretical model. Section 3.3 focus on the long-term equilibria of the economy. The implications of the environmental policy on the dynamics and growth are examined in Section 3.4. In Sections 3.3 and 3.4, we provide analytical results followed by a numerical illustration. Finally, Section 3.5 concludes and technical details are relegated to an Appendix.

3.2 The model

Consider an overlapping generations economy, with discrete time indexed by $t = 0, 1, 2, ..., +\infty$. Households may live three periods, childhood, adulthood, and old age depending on a longevity index. At each date t, a new generation of N heterogeneous agents is born. We assume no population growth, so we normalize the size of the population (N) to unity. Individuals are indexed by $i = u, s$, corresponding to the two groups of workers in the economy, lower-skilled (u) and higher-skilled (s), of size ξ and $1 - \xi$ respectively.[7] The two groups of agents are characterized by an inequality in initial endowment in terms of human capital, so that agents born in $t - 1$ differ only in the human capital level of their parents ($h^u_{t-1} < h^s_{t-1}$).

[7] The reason why we refer to lower-skilled individuals as u and to higher-skilled individuals as s is that the first category is relatively unskilled while the second is relatively skilled.

3.2.1 Consumer's behavior

Individual of type i born in $t-1$ cares abouts her adult consumption level c_t^i, her old-age consumption level d_{t+1}^i and about the future level of human capital of her child through paternalistic altruism h_{t+1}^i. Preferences are represented by the following utility function:

$$\ln(c_t^i) + \pi_t^i \left[\beta \ln(d_{t+1}^i) + \gamma \ln(h_{t+1}^i)\right] \tag{3.1}$$

with γ and $\beta > 0$.

The weight π_t^i represents the agent's longevity or her survival probability in old age.[8] A higher life expectancy enhances the welfare obtained from consuming when old, but also from the future human capital of her child. Therefore, parents value more the future, for them and for their children, when they live longer. Reversely, parents with shorter life expectancy have shorter time horizons and hence put less weight on investment whose return is future (including the future human capital of their children), not necessarily because they are less altruistic but because they simply assess differently what is good for their children.[9] Note that, this assumption enables the longevity to affect positively investments in education, in accordance with empirical evidence (see *e.g.* Jayachandran & Lleras-Muney , 2009 or Hansen , 2013).

Longevity is an index of health status assumed to depend on individual's human capital h_t^i and pollution P_t in accordance with empirical evidence. As we mentioned in the Introduction, the effect of human capital on health has been well established in empirical studies and is explained by the fact that higher human capital mostly involves

[8] Since individual i born in $t-1$ lives $2+\pi_t^i$, we interchangeably use the terms "life expectancy", "longevity" and "survival probability" in the paper. We will also refer to it as health, although it is just one measure of health among others.

[9] Alternatively, Mariani *et al.* (2010) explain that parents will be relatively more affected by the success or the failure of their children if they live long enough to witness it. The same formalization is also adopted by Osang & Sarkar (2008).

better living and working conditions, better access to healthcare and better information about health problems and prevention (see e.g. Kenkel , 1991 or Lleras-Muney , 2005). Whereas, in the same way, there is considerable evidence that pollution has a positive and significant effect on mortality, whether it goes through air, water, soil *etc.* (see e.g. Pimentel *et al.* , 1998; Bell & Davis , 2001; Pope *et al.* , 2002 ; Bell *et al.* , 2004 or Evans & Smith , 2005). For the sake of simplicity, we assume a functional form for the life expectancy index, which is in line with the form adopted by Blackburn & Cipriani (2002), Chakraborty (2004), Castello-Climent & Domenech (2008) or Raffin & Seegmuller (2014):

Assumption 2

$$\pi_t^i = \pi\left(\frac{h_t^i}{P_t}\right) = \frac{\sigma h_t^i/P_t}{1 + h_t^i/P_t} \tag{3.2}$$

with $\sigma \in (0,1]$*, the upper bound of longevity. Thus,* $\pi_t \in [0,1]$*,* $\pi'(h_t^i/P_t) > 0$ *and* $\pi''(h_t^i/P_t) < 0$.

During childhood, individuals are reared by her parents and do not make any decisions. When adult, they supply inelastically one unit of labor remunerated at the wage w_t per unit of human capital. They allocate this income to consumption c_t^i, savings s_t^i and education of their children.

We assume that the education of a child requires that her parent invests $e_t^i\bar{h}_t$ units of human capital, such that schooling time e_t^i corresponds to an opportunity cost for the parent of $e_t^i\bar{h}_t w_t$ (as she does not use this efficient labor in production). Therefore, the total cost of education is the same for all types of agents and is relatively more expensive for poor parents.[10] When old, agents only consume. In line with Yaari (1965), Blanchard (1985) or Chakraborty (2004), we assume a perfect annuity market to abstract from

[10]This assumption is perfectly equivalent to the one of de la Croix & Doepke (2003) or Schaefer (2014), where education is provided by teachers with a level of human capital equal to the average in the economy.

the risk associated with uncertain lifetimes. Therefore, households deposit their savings to a mutual fund, which invests these amounts in physical capital. In return, the mutual fund provides them an actuarially fair annuity during retirement, corresponding to their savings increased by the gross return adjusted from their life expectancy R_{t+1}/π_t^i.

The two budget constraints for an adult born in $t-1$ are:

$$c_t^i + e_t^i \bar{h}_t w_t + s_t^i = w_t h_t^i \tag{3.3}$$

$$d_{t+1}^i = \frac{s_t^i R_{t+1}}{\pi_t^i} \tag{3.4}$$

Human capital of her child h_{t+1}^i depends on the education e_t^i, human capital of the parents h_t^i and average human capital $\bar{h}_t$, representing the quality of the school system.

$$h_{t+1}^i = \epsilon (e_t^i)^\mu (h_t^i)^\eta (\bar{h}_t)^{1-\eta} \tag{3.5}$$

with $\epsilon > 0$, the efficiency of human capital accumulation. The parameters μ, η and their sum $\mu + \eta$ all $\in (0,1)$.[11] They are compatible with endogenous growth and capture respectively the efficiency of education and the intergenerational transmission of human capital within the family relatively to the transmission within the society.

The consumer program is summarized by:

$$\max_{e_t^i, s_t^i}, U(c_t^i, d_{t+1}^i, h_{t+1}^i) = \ln c_t^i + \pi_t^i \left[\beta \ln(d_{t+1}^i) + \gamma \ln(h_{t+1}^i)\right] \tag{3.6}$$

$$s.t \quad c_t^i + e_t^i w_t \bar{h}_t + s_t^i = w_t h_t^i$$

[11] We assume that $\mu + \eta < 1$ so that human capital convergence is possible. Education choice depends positively on h_t^i and negatively on $\bar{h}_t$ (representing the cost of education). Therefore, if $\mu + \eta > 1$, the return of h_t^i is always increasing and the return of $\bar{h}_t$ is negative, such that human capital convergence is impossible.

$$d^i_{t+1} = \frac{s^i_t R_{t+1}}{\pi^i_t}$$

$$h^i_{t+1} = \epsilon (e^i_t)^{\mu} (h^i_t)^{\eta} (\bar{h}_t)^{1-\eta}$$

The maximization of this program (3.6) leads us to the following optimal choices in terms of education and savings.

$$e^i_t = \frac{\pi^i_t \gamma \mu}{1 + \pi^i_t(\beta + \gamma\mu)} \frac{h^i_t}{\bar{h}_t} \tag{3.7}$$

$$s^i_t = \frac{\pi^i_t \beta}{1 + \pi^i_t(\beta + \gamma\mu)} w_t h^i_t \tag{3.8}$$

Higher-skilled households invest more in savings and in children's education than lower-skilled households. The reason for this is twofold. First, there is a traditional income effect. The total wage of a worker depends on the wage rate w_t, equal for all agents, and on the level of human capital of this worker h^i_t. Therefore, higher-skilled parents benefit from a higher pay than lower-skilled one and can afford to spend more on education and savings. Second, longevity plays also an important role in the optimal choices for education and savings. An individual living a longer time gives more weight to the future. She saves more to consume during the extended retirement period and invests more in her child education, as she value more the future and will witness the returns of this investment. Moreover, as stated above, individuals with higher education are likely to live longer, mainly because they have better access to healthcare and are better informed, which allow them to adopt healthier behaviors and to suffer less from the negative health effects of pollution. Therefore, human capital disparities imply inequalities in life expectancy and hence in preferences for the future, which translates into larger preferences of higher-skilled households for savings and children's education. Both the longevity effect and the income effect reinforce the persistence of human capital disparities.

One can notice that the optimal choice in terms of child's education is determined by the relative human capital of parents (with respect to the average level of human capital in the economy) rather than by the absolute level. The rational for this is that education implies an opportunity cost associated with the investment in human capital agents have to do to educate their children. This investment is the same for all and is equal to the average human capital in the economy, in order to represent a standardized educational system (where a unit of schooling time is equivalent for all types of agents). Thus, it implies that the schooling time parents choose for their children depends on their relative human capital and will be relatively more expensive for the lower-skilled parents.

3.2.2 Production

Production of the consumption good is carried out by a single representative firm. The output is produced according to a constant returns to scale technology:

$$Y_t = AK_t^{\alpha} L_t^{1-\alpha} \tag{3.9}$$

where K_t is the aggregate stock of physical capital, L_t is the aggregate efficient labor supply to production, $A > 0$ measures the technology level, and $\alpha \in (0, 1)$ is the share of physical capital in the production. Defining $y_t \equiv \frac{Y_t}{L_t}$ as the output per unit of labor and $k_t \equiv \frac{K_t}{L_t}$ as the capital labor ratio, we have the following production function per unit of labor:

$$y_t = Ak_t^{\alpha}$$

The government collects revenues through a tax rate $0 \leqslant \tau < 1$ on production, which is the source of pollution. The firm chooses inputs by maximizing profits $(1-\tau)Y_t - R_tK_t - w_tL_t$, such that:

$$w_t = A(1-\alpha)(1-\tau)k_t^{\alpha} \tag{3.10}$$

$$R_t = A\alpha(1-\tau)k_t^{\alpha-1} \tag{3.11}$$

3.2.3 Pollution

In this paper, we focus on the effect of pollution on health. Considering air pollution which represents the world's largest single environmental health risk according to the World Health Organization, we notice that its direct harmful effect on human health corresponds to the level before absorption, deposition or dispersion in the atmosphere. Moreover, the air pollutants identified as the most significant health threats, i.e. particulate matter and ground-level ozone, remain in the atmosphere only for short periods of time (from hours to weeks). Thus, focusing on direct effects of pollution on health, we choose to consider pollution as the flow currently emitted in the economy.[12] The same choice has been done theoretically by Pautrel (2008) and Aloi & Tournemaine (2013) among others.

Environmental degradation is a by-product of the current production process ($Y_t = y_tL_t$). The government can use the revenue of the pollution tax (τ) to reduce pollution, by providing a public environmental maintenance $M_t > 0$. This public maintenance, also called pollution abatement, represents a public investment in favor of the environment. Considering air pollution, governments may implement clean air strategies to reduce the use of fossil fuels through investment in renewable energy or subsidy of green

[12]Considering pollution as a stock rather than a flow would increase the effect of pollution on health and the importance of environmental policy, but would make the model much more complicated.

transportation (public and private) for example.

Keeping in mind that we focus mainly on air pollution, it is clear that such environmental damage is not exclusively due to production activities but also to transportation, energy consumption *etc*. Thus, in order to consider the effect of the whole economic activity on pollution, we weight the pollution flow by the total labor force ($\bar{h}_t$) over the labor used in the production of the consumption good (L_t). Therefore, we define the law of motion of pollution as:

$$P_t = (ay_tL_t - bM_t)\,\frac{\bar{h}_t}{L_t} \tag{3.12}$$

where the parameters $a > 0$ and $b > 0$ correspond to the rate of pollution flow and the efficiency of environmental maintenance respectively.

The government budget is balanced at each period such that the level of public environmental maintenance is equal to $M_t = \tau y_t L_t$. Then, the pollution flow at a period t can be rewritten as:

$$P_t = (a - b\tau)y_t\bar{h}_t \tag{3.13}$$

Thus, pollution is composed of two elements. While production per unit of efficient labor y_t (which depends on capital intensity k_t) represents an index of pollution intensity, the aggregate human capital $\bar{h}_t$ corresponds to a “scale effect". Indeed, even if human capital is not pollutant *per se*, it defines the scale of economic activities and hence of pollution emissions.

In order to ensure that human activities lead to a positive pollution flow regardless the tax level, we assume:

Assumption 3 $a > b$

3.3 Equilibrium

The market clearing conditions for capital and labor are given by:

$$K_{t+1} = \xi s_t^u + (1-\xi) s_t^s \tag{3.14}$$

and

$$L_t = \xi[h_t^u - e_t^u \bar{h}_t] + (1-\xi)[h_t^s - e_t^s \bar{h}_t] \tag{3.15}$$

The presence of $e_t^i \bar{h}_t$ illustrates the investment of parents in terms of human capital, which does not enter the production of the consumption good. The values of e_t^i and s_t^i are given by the optimal choices of consumers (3.7) and (3.8) with the wage corresponding to (3.10). Thus, the market clearing conditions can be rewritten as:

$$K_{t+1} = A(1-\alpha)(1-\tau)k_t^\alpha \left[\xi h_t^u \frac{\pi_t^u \beta}{1+\pi_t^u(\beta+\gamma\mu)} + (1-\xi) h_t^s \frac{\pi_t^s \beta}{1+\pi_t^s(\beta+\gamma\mu)}\right] \tag{3.16}$$

and

$$L_t = \bar{h}_t \left[\xi x_t^u \frac{1+\pi_t^u \beta}{1+\pi_t^u(\beta+\gamma\mu)} + (1-\xi) x_t^s \frac{1+\pi_t^s \beta}{1+\pi_t^s(\beta+\gamma\mu)}\right] \tag{3.17}$$

The variable $x_t^i \equiv \frac{h_t^i}{\bar{h}_t}$ corresponds to the relative human capital of an individual i in period t. Using (3.5), the relative human capital of her child is described by:

$$x_{t+1}^i = \epsilon \left(\frac{\pi_t^i \gamma \mu x_t^i}{1+\pi_t^i(\beta+\gamma\mu)}\right)^\mu \frac{1}{g_t}(x_t^i)^\eta \tag{3.18}$$

with $g_t \equiv \frac{\bar{h}_{t+1}}{\bar{h}_t}$, the growth factor of average human capital. From the definition of the average human capital ($\bar{h}_t = \xi h_t^u + (1-\xi) h_t^s$), we can deduce the expression of the growth of human capital:

$$g_t = \epsilon(\gamma\mu)^{\mu}\left[\xi\left(\frac{\pi_t^u}{1+\pi_t^u(\beta+\gamma\mu)}\right)^{\mu}(x_t^u)^{\mu+\eta}+(1-\xi)\left(\frac{\pi_t^s}{1+\pi_t^s(\beta+\gamma\mu)}\right)^{\mu}(x_t^s)^{\mu+\eta}\right] \tag{3.19}$$

And the pollution flow corresponds to:

$$P_t = (a-b\tau)Ak_t^{\alpha}\,\bar{h}_t \tag{3.20}$$

We can rewrite the longevity given in (3.2) in terms of the individual relative human capital and of the capital-labor ratio:

$$\pi_t^i = \pi\left(\frac{x_t^i}{P_t/\bar{h}_t}\right) = \frac{\sigma x_t^i}{(a-b\tau)Ak_t^{\alpha}+x_t^i} \tag{3.21}$$

Equations (3.16), (3.17) and (3.18) characterize the dynamics of the economy.

Definition 5. *Given the initial condition $K_0 \geqslant 0$, $h_0^u \geqslant 0$ and $h_0^s \geqslant 0$, the intertemporal equilibrium is the sequence $(k_t, x_t^u, x_t^s)_{t\in\mathbb{N}}$ such that the following dynamic system is satisfied for all $t \geqslant 0$:*

$$\left\{\begin{array}{lcl} k_{t+1} & = & \frac{A(1-\tau)(1-\alpha)k_t^{\alpha}}{g_t}\left[\xi x_t^u\frac{\pi_t^u\beta}{1+\pi_t^u(\beta+\gamma\mu)}+(1-\xi)x_t^s\frac{\pi_t^s\beta}{1+\pi_t^s(\beta+\gamma\mu)}\right] \\ & & \left[\xi x_{t+1}^u\frac{1+\pi_{t+1}^u\beta}{1+\pi_{t+1}^u(\beta+\gamma\mu)}+(1-\xi)x_{t+1}^s\frac{1+\pi_{t+1}^s\beta}{1+\pi_{t+1}^s(\beta+\gamma\mu)}\right]^{-1} \\ x_{t+1}^u & = & \epsilon\left(\frac{\pi_t^u\gamma\mu}{1+\pi_t^u(\beta+\gamma\mu)}\right)^{\mu}\frac{1}{g_t}(x_t^u)^{\mu+\eta} \\ x_{t+1}^s & = & \epsilon\left(\frac{\pi_t^s\gamma\mu}{1+\pi_t^s(\beta+\gamma\mu)}\right)^{\mu}\frac{1}{g_t}(x_t^s)^{\mu+\eta} \end{array}\right. \tag{3.22}$$

with g_t and π_t^i given by (3.19) and (3.21) respectively.

The evolution of the economy is summarized by the laws of motion of the physical to labor ratio (k), and of the relative human capital of lower-skilled agents (x^u) and higher-skilled agents (x^s). We can rewrite the dynamical system (3.22) by substituting the growth of the average human capital by its expression given in (3.19). Moreover, from the definition of average human capital, we can express the relative human capital of higher-skilled x_t^s as a function of the one of lower-skilled workers: $\frac{1-\xi x_t^u}{1-\xi}$. After some computations, it follows that the dynamical system given in Definition 5 can be simplified as a two dimensions system in terms of the capital-labor ratio in the production of the consumption good k and the relative human capital of lower-skilled agents x^u.

$$\begin{cases} k_{t+1} = \frac{A(1-\tau)(1-\alpha)k_t^\alpha}{\epsilon(\gamma\mu)^\mu}\left[\xi x_t^u \frac{\pi_t^u\beta}{1+\pi_t^u(\beta+\gamma\mu)} + (1-\xi x_t^u)\frac{\pi_t^s\beta}{1+\pi_t^s(\beta+\gamma\mu)}\right] \\ \quad \left[\xi x_{t+1}^u \frac{1+\pi_{t+1}^u\beta}{1+\pi_{t+1}^u(\beta+\gamma\mu)} + (1-\xi x_{t+1}^u)\frac{1+\pi_{t+1}^s\beta}{1+\pi_{t+1}^s(\beta+\gamma\mu)}\right]^{-1} \\ \quad \left[\xi\left(\frac{\pi_t^u}{1+\pi_t^u(\beta+\gamma\mu)}\right)^\mu (x_t^u)^{\mu+\eta} + (1-\xi)\left(\frac{\pi_t^s}{1+\pi_t^s(\beta+\gamma\mu)}\right)^\mu\left(\frac{1-\xi x_t^u}{1-\xi}\right)^{\mu+\eta}\right]^{-1} \\ x_{t+1}^u = (x_t^u)^{\mu+\eta}\left(\frac{1-\xi x_t^u}{1-\xi}\right)^{-\mu-\eta}\left(\frac{1-\xi x_{t+1}^u}{1-\xi}\right)\left(\frac{\pi_t^u}{1+\pi_t^u(\beta+\gamma\mu)}\right)^\mu\left(\frac{\pi_t^s}{1+\pi_t^s(\beta+\gamma\mu)}\right)^{-\mu} \end{cases} \tag{3.23}$$

with π_t^i given by (3.21).

Given the definitions of the average human capital and of the relative human capital, a decrease in the relative human capital of lower-skilled individuals x^u is due to a decrease in the level of human capital of lower-skilled h^u and/or to an increase in the level of human capital of higher-skilled individuals h^s. Moreover, a decrease in the lower-skilled relative human capital corresponds to a proportional increase in the higher-skilled relative human capital. Therefore, the lower x^u is, the lower is the level of human capital of lower-skilled workers respectively to higher-skilled workers, and hence the wider are disparities. Consequently, we use the relative human capital of lower-skilled individuals

x^u to approximate the level of inequalities in the economy.

In this section, we aim to analyze the long-run behavior of the economy. Thus, from Definition 5, we specify:

Definition 6. *A balanced growth path (BGP) is an equilibrium satisfying Definition 5 and where the stock of physical and human capital grow at the same and constant rate $(g-1)$.*

At a balanced growth path, the capital-labor ratio k_t, the growth of average human capital g_t, the relative human capital x_t^i and the flow of pollution P_t are constant.

For technical reasons, the study of the existence of balanced growth path equilibria is done in two parts. First, we analyze the case where $x^u = x^s = 1$, at which there is no inequality at the BGP. Second, we look at the case where $x^u \neq x^s \neq 1$, which means reversely that inequalities exist among households at the BGP.[13]

3.3.1 BGP without inequality: $x^u = x^s = 1$

We examine first the existence of a BGP equilibrium where there is no inequality. In this case, all individuals have the same human capital ($h_t^u = h_t^s = \bar{h}_t$), hence all the relative human capital levels x_t^i are equal to 1. The dynamics of the economy described in (3.23) when $x^u = x^s = 1$ reduces to:

$$k_{t+1}\frac{1+\beta\pi_{t+1}}{1+\pi_{t+1}(\beta+\gamma\mu)} = \frac{A(1-\tau)(1-\alpha)\beta k_t^{\alpha}}{\epsilon(\gamma\mu)^{\mu}}\left[\frac{\pi_t}{1+\pi_t(\beta+\gamma\mu)}\right]^{1-\mu} \tag{3.24}$$

with $\pi_t = \frac{\sigma}{1+(a-b\tau)Ak_t^{\alpha}}$.

From this dynamical equation, we obtain that:

[13]When $x = 1$, rewrite the system (3.23) as two functions of k depending on x^u requires to divide by zero in the second dynamical equation.

Proposition 8 *Under Assumptions 2 and 3 and the conditions $\alpha < \frac{1}{2}$ and $\epsilon > \bar{\epsilon}$, there exists a balanced growth path without inequality $(k_E, 1, 1)$ with a positive growth rate $(g_E - 1 > 0)$. This BGP is locally stable when $\eta < \bar{\eta}(\tau)$ and corresponds to a saddle point otherwise. The thresholds $\bar{\epsilon}$ and $\bar{\eta}(\tau)$ correspond to:*[14]

$$\bar{\epsilon} \equiv \left[\frac{(a-b\tau)Ak_E^{\alpha} + 1 + \sigma(\beta+\gamma\mu)}{\sigma\gamma\mu}\right]^{\mu} \quad \text{and} \quad \bar{\eta}(\tau) \equiv 1 - \mu\frac{2(a-b\tau)Ak_E^{\alpha} + (1+\sigma(\beta+\gamma\mu))}{(a-b\tau)Ak_E^{\alpha} + (1+\sigma(\beta+\gamma\mu))}$$

Note that the BGP without inequality is always stable if $\mu + \eta \to 0$ and is always a saddle point if $\mu + \eta \to 1$.

Proof. See Appendix 3.6.1. ■

From this proposition, we know that human capital accumulation has to be sufficiently efficient ($\epsilon > \bar{\epsilon}$) so that the growth rate is positive at the long-term state without inequality. Most importantly, we see that the economy may converge in the long run to a balanced growth path without inequality among households.[15] But it is not always the case. When the equilibrium is a saddle point ($\eta > \bar{\eta}(\tau)$), the convergence toward the long-term equilibrium without inequality is very unlikely. Thus, the economy will most likely exhibit inequalities in the long run.[16]

Several effects intervene against and in favor of the human capital convergence. The model combines channels usually found in the literature on human capital and inequality (e.g. Tamura , 1991, Glomm & Ravikumar , 1992 or de la Croix & Doepke , 2003) and the more uncommon longevity channel (see Castello-Climent & Domenech , 2008 for an exception).[17] First, the presence of parents' human capital in the production of children's

[14] The effect of τ on $\bar{\eta}(\tau)$ is detailed in Section 3.4.1.

[15] Such equilibrium is possible because agents differ only in the initial level of human capital. We do not assume in this model that poor individuals are less able to acquire skills.

[16] Note that by definition $0 \leqslant x^u \leqslant 1$. Therefore, the economy can achieve the BGP where $x^u = 1$ only for few initial conditions where x_0^u is very high and k_0 is very low. We analyze the extent of inequalities when $(k_E, 1, 1)$ is unstable in Section 3.3.3, after determining if there are also BGP with inequalities.

[17] Castello-Climent & Domenech (2008) isolate the life expectancy channel by considering that hu-

knowledge acts as a divergent force. This intergenerational spillover results directly in the transmission of inequalities and hence in their persistence over time. Then, this channel is reinforced by two other divergent forces leading to disparities in education choices among parents. The income differential among parents, due to inequalities in their human capital, implies that lower-skilled individuals can less afford the cost of educating their children. Moreover, the life expectancy of an individual determines her preference for the future and in particular for her child's education. In our model, longevity is endogenous and depends on individual human capital and pollution. It follows that lower-skilled agents have also a poor health and give less value to education. The reverse occurs for higher-skilled parents who are more able and willing to finance education. Thus, the gap among children's future human capital is widened by these divergent forces (through intergenerational transmission and education). Finally, on the opposite, the presence of average human capital in the production of human capital represents a convergent force, which is crucial to ensure that human capital convergence is possible, as Tamura (1991) shows. In other words, the quality of the school system has to be at least partly the same for all children in the economy, so that they can achieve the same level of human capital in long run.

According to these effects, it emerges that the weight of the divergent forces, i.e. of education and intergenerational transmission, in human capital accumulation has to be not too high in order to avoid that poor agents are further disadvantaged and hence that the poor-rich gap gets worse. Thus, we identify a condition in terms of the weight of intergenerational transmission in the production of human capital so that the economy can converge to an equilibrium where inequalities vanish ($\eta < \bar{\eta}(\tau)$). Moreover, if the sum of the weight of education and intergenerational transmission in human capital is at its maximum ($\mu + \eta \to 1$), the long-term equilibrium without inequality is always a

man capital formation depends only on an investment in time. Thus, they do not consider the other aforementioned effects.

saddle point, as the convergent force is eliminated. Reversely, when it is at its minimum ($\mu + \eta \to 0$), the BGP is always stable as divergent forces are removed.

Note that the dispersion through the longevity channel will be even larger when pollution is high. Lower-skilled households being more vulnerable to pollution than higher-skilled households, the environmental damages amplify health disparities and hence human capital inequalities. Thus, the levels of both inequalities and pollution intensity in the economy modify the return on investment in education and favor the persistence of inequalities and hence could play a key role in the determination of the long-term behavior of the economy. However, we need to know if there are other BGP to conclude precisely on this point, which is what we do in the rest of the section.

3.3.2 BGP with inequalities: $x^u \neq x^s$

At an equilibrium with inequalities, the two groups of individuals (lower- and higher-skilled) have not the same human capital ($h_t^u < \bar{h}_t < h_t^s$), hence the relative human capital of each goup x_t^i differs from 1. By developing the dynamical system (3.22) with the explicit form of longevity given in (3.21), we can rewrite the system at a balanced growth path with inequalities as:

$$\begin{cases} k^{1-\alpha} \frac{\epsilon(\sigma\gamma\mu)^\mu}{A(1-\tau)(1-\alpha)\beta} \left[\frac{\left[(a-b\tau)Ak^\alpha + \frac{1-\xi x^u}{1-\xi}(1+\sigma\beta)\right]\left[(a-b\tau)Ak^\alpha + x^u(1+\sigma(\beta+\gamma\mu))\right] + \xi x^u (a-b\tau)Ak^\alpha \sigma\gamma\mu\left(\frac{1-\xi x^u}{1-\xi} - x^u\right)}{(a-b\tau)Ak^\alpha \sigma\left(\frac{(1-\xi x^u)^2}{1-\xi} + \xi (x^u)^2\right) + \frac{1-\xi x^u}{1-\xi}\sigma x^u (1+\sigma(\beta+\gamma\mu))} \right] \\ \left[\frac{\xi (x^u)^{2\mu+\eta}}{\left[(a-b\tau)Ak^\alpha + x^u(1+\sigma(\beta+\gamma\mu))\right]^\mu} + \frac{(1-\xi)\left(\frac{1-\xi x^u}{1-\xi}\right)^{2\mu+\eta}}{\left[(a-b\tau)Ak^\alpha + \left(\frac{1-\xi x^u}{1-\xi}\right)(1+\sigma(\beta+\gamma\mu))\right]^\mu} \right] - 1 = 0 \\ k = \left[\frac{1+\sigma(\beta+\gamma\mu)}{(1-\xi)A(a-b\tau)} \frac{(1-\xi)x^u (1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}} - ((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}}(1-\xi x^u)}{((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}} - (1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}}} \right]^{\frac{1}{\alpha}} \end{cases} \tag{3.25}$$

The study of this system results in the following proposition on the existence of balanced growth paths with inequalities:

Proposition 9 *Under Assumptions 2 and 3, for* $2\mu + \eta > 1$ *and* $\alpha < 1/2$*, there exists at least one BGP with inequalities when* $A < \bar{A}(\tau)$*, with :*[18]

$$\bar{A}(\tau) \equiv \left\{ \frac{\epsilon(\gamma\mu)^{\mu}}{(1-\tau)(1-\alpha)\beta\sigma^{1-\mu}} \left[\frac{2\mu+\eta-1}{\mu(1+\sigma(\beta+\gamma\mu))} \right]^{\mu} \left[\frac{1+\sigma(\beta+\gamma\mu)}{(a-b\tau)} \frac{1-\mu-\eta}{2\mu+\eta-1} \right]^{\frac{1-\alpha}{\alpha}} \left[\frac{\sigma\gamma\mu(1-\mu-\eta)+(1+\beta\sigma)\mu}{2\mu+\eta-1} \right] \right\}^{\alpha}$$

Note that there is no BGP with inequalities in the extreme case where $\mu + \eta \to 0$*.*

Proof. See Appendix 3.6.2. ■

While there always exists a balanced growth without inequality, one or several balanced growth path(s) characterized by inequalities among households may also occur. More precisely, it is the case at least for a total factor productivity not too high. At such a long-term state, human capital and longevity of individuals diverge across lower- and higher-skilled individuals in the long run. The existence of a balanced growth path with inequalities stems from the balance between the convergent force and the divergent forces in the formation of human capital, that we have mentioned in the previous section. In particular, from the condition $A < \bar{A}(\tau)$, it follows that when the weights of intergenerational spillover and dispersion in education choices, corresponding to the divergent forces, are zero ($\mu + \eta \to 0$), there is no BGP with inequalities and the only long-term equilibrium is the BGP without inequality, which is stable in this case.[19] Thus, as we explained previously, the weight of the divergent forces has to be sufficiently high so that inequalities can persist in the economy in the long run.

[18]The effect of τ on $\bar{A}(\tau)$ is detailed in Section 3.4.1.

[19]A further analysis of the condition under which BGP with inequalities exist(s) is provided in the numerical illustration in Section 3.3.3.

More particularly, the existence of multiple balanced growth paths and in particular of an inequality trap, where disparities among households are persistent or widening across time, results from the fact that longevity is endogenous in our model. The life expectancy of an individual depends on her level of human capital and the aggregate level of pollution. Therefore, pollution and human capital affect the returns of investment in education through health. Indeed, at an individual level, more pollution or less human capital entail that she will die sooner, hence her preferences for the future are lower and she benefits less from her investment in her child education. Moreover, lower-skilled agents are more vulnerable to the negative effect of pollution on health than higher-skilled agents. Thus, the initial levels of pollution and inequalities shape the extent of disparities in terms of health and return to education, and thus the level of inequalities for the next generation. More precisely, pollution and inequalities determine if the growth of individual human capital is higher for lower-skilled or higher-skilled households. Usually in the literature on human capital and inequality, it is always higher for lower-skilled under the diminishing return of the divergent forces in human capital accumulation (equivalent to the condition $\mu + \eta < 1$ in our model), so that human capital convergence occurs (see e.g. Tamura , 1991 or Glomm & Ravikumar , 1992).[20] In our model, despite the condition $\mu + \eta < 1$, it is not always the case. When the levels of pollution and/or inequalities are too high, the growth of individual human capital can be lower or equal for lower-skilled, which implies that there exists an inequality trap.[21] Therefore, the extent of the dispersion through the longevity channel, and more generally of the divergent forces, varies according to the initial conditions of the economy in terms of pollution and inequalities, which are then determinant for its behavior in the long run. Note that

[20] In Glomm & Ravikumar (1992), when education is public, human capital convergence always occurs, while when education is private, it is the case when the sum of the weights of private spending in education and of intergenerational transmission in human capital formation are lower than 1.

[21] The individual growth of human capital g^i is increasing and then decreasing in x^i. The maximum value of g^i is achieved in $x^i < 1$, while $g^i(0) = 0$ and $g^i(Max\{x^s\}) > 0$. Thus, there exists a level of x^u under (resp. above) which the individual growth of human capital is lower (resp. higher) for lower-skilled than higher-skilled agents $g^u < g^s$ (resp. $g^u > g^s$).

if longevity would be exogenous in our model, the growth of individual human capital would always be higher for lower-skilled so that the economy would always converge to the long-term equilibrium without inequality (under $\mu + \eta < 1$).

Analytically, we are not able to conclude on the dynamics of the long-term equilibrium(a) with inequalities. However, it is important to identify what scenario will take place and under what conditions, that is why we will analyze numerically the number and the characteristics of the balanced growth path(s) with inequalities in the next section.

3.3.3 Numerical illustration

In this section, we provide a numerical analysis of the model in order to describe more precisely the long-term behaviors of the economy. After motivating the choice of the parameters value, we study in details the characteristics of the different balanced growth paths.

Calibrations

To solve the model numerically, we give values to the parameters of technology and preferences so that they fit empirical observations and projections of the US economy. We calibrate the model assuming that a period represents thirty years. Therefore, an individual starts working at 30, retires at 60 and may live for up to 90, according to her longevity. In the real-business-cycle literature, the quarterly psychological discount factor is estimated to 0.99 (see Cooley , 1995 or de la Croix & Michel , 2002). A period representing 30 years in our model, β is set to $0.99^{120} = 0.3$. We choose parameters to match US data on the annual long-term growth rate (i.e. around 1.7%) and the US share of education expenditure in GDP at the balanced growth path (i.e. between 5 and

8%).[22] Thus, considering that the two groups of workers have the same size ($\xi = 0.5$)[23], we set the scale parameter ϵ to 6 and the preference for child human capital γ to 0.35.

The parameter μ represents the weight of education in human capital accumulation and corresponds more precisely in our model to the elasticity of human capital with respect to education. In the literature, the return to schooling in developed countries is estimated between 8% and 16% (see Ashenfelter & Krueger , 1994; Psacharopoulos , 1994 or Krueger & Lindahl , 2001). These figures correspond to Mincerian returns, which means that they include only an opportunity cost (forgone earnings) and do not consider education expenditure. Following de la Croix & Doepke (2003), we assume that an additional year of schooling raises education expenditure by 20%. The resulting elasticity of schooling is from 0.4 to 0.8. Thus, we set μ to be 0.6. The weight of intergenerational transmission of human capital η being a key parameter in our analysis, we will consider all values allowed by the model, i.e. $\eta \in [0, 1-\mu)$.

The weight of production in the pollution flow and of environmental maintenance are chosen to satisfy the condition $a > b$, ensuring that there is pollution emission in the presence of economic activities, i.e. $a = 0.6$ and $b = 0.4$. The parameter in the longevity function σ is set to 0.9, so that the values of individuals' life expectancy at the balanced growth paths corresponds to realistic values (between 60 and 87 years).[24] Finally, concerning the production technology, the share of physical capital in the production of the consumption good α is set to 1/3 in accordance with empirical data, and the total factor productivity A is a scale parameter set to 1. Note that the value of A with those of the other parameters, allows that the condition $A < \bar{A}(\tau)$, such that there exists at least one BGP with inequality, is always satisfied for a sufficient level of the tax $\tau \in [0, 1)$.

[22] See the long-term projections for the US economy of OECD (2014a) on the growth rate and the Digest of Education Statistics 2012 of the US Department of Education for data on the education share.

[23] We will provide a sensitivity analysis with respect to the repartition of the population between the two groups ξ in Appendix 3.6.5.

[24] While the lower bound is equivalent to the US life expectancy at birth in the thirties, the upper bound is close the value expected by the US Census Bureau for 2060 (84 years).

Long-term behaviors of the economy

First, we identify the different long-term equilibria of the calibrated economy and we compare their characteristics. For the set of parameters considered, we obtain:[25]

Numerical result 1 *(i) When $\eta > \bar{\eta}(\tau)$, there exists a unique BGP, which is the one without inequality $(k_E, 1, 1)$. (ii) When $\eta < \bar{\eta}(\tau)$, there exist multiple balanced growth paths: the BGP without inequality $(k_E, 1, 1)$ and an additional BGP with inequalities (k_I, x_I^u, x_I^s).*
The two long-term equiliria are characterized by:

- $x_I^s > 1 > x_I^u$
- $k_I > k_E$
- $\pi_I^s > \pi_E > \pi_I^u$ *and* $\pi_E > \bar{\pi}_I$
- $g_E > g_I$

First, it is worth noticing that the numerical analysis enables us to identify how many and when the BGP with inequalities exist(s). We find that one equilibrium with inequalities may exist, and more interestingly, that it is the case under the threshold $\bar{\eta}(\tau)$, identified in Proposition 8. Therefore, we have that, in the numerical illustration, this threshold corresponds to the value under which the equilibrium without inequality is stable and under which the balanced growth path with inequalities appears, for all the levels of the tax.

Concerning the characteristics of the economy, the long-term equilibrium with inequalities corresponds to a state where there are persistent inequalities among households in the economy. Higher-skilled agents are characterized by a higher level of human capital than lower-skilled agents ($x_I^s > 1 > x_I^u$). Moreover, at this state, the capital labor

[25] All the numerical results are obtained by considering the parameters η and τ with a pitch value of 0.000001 unit.

ratio is higher ($k_I > k_E$), which implies that the pollution intensity is also larger in I. This is essentially due to the fact that average savings increase with inequalities, as they are convex in the level of relative human capital. Due to a higher dispersion of human capital and a higher pollution intensity at the BGP with inequalities, it follows that disparities in terms of health are also higher at this equilibrium. While lower-skilled agents have a lower relative human capital and suffer from the higher pollution intensity, higher-skilled workers benefit from an increase in their relative human capital, which more than offsets the increase in the pollution intensity. Therefore, at the balanced growth path I, rich individuals live much longer than poor individuals ($\pi_I^u < \pi_E < \pi_I^s$). Moreover, the average life expectancy in the economy is higher at the long-term equilibrium without inequality (π_E) than at the one with inequalities ($\bar{\pi}_I$), which means that the health cost of inequalities for poor is higher than the benefit for rich.

Concerning the long-term growth which is driven by human capital, we obtain that it is higher at the balanced growth path without inequality ($g_E > g_I$). Several effects occur. The average education is higher at the long-term equilibrium with inequalities I, as education is convex in the relative human capital. In other words, the increase in the education choice of higher-skilled parents, due to their higher longevity and income, outweighs the decrease in the education choice of lower-skilled parents, arising from lower longevity and income. However, human capital accumulation depends also on the relative human capital they transmit to their children. At the BGP with inequalities, the associated dispersion harms more lower-skilled than it benefits to higher-skilled. The net effect is that the long-term growth is higher in the absence of inequalities. Therefore, inequalities have a cost in terms of growth and development in addition to their human cost.

This result is supported by empirical evidence: OECD (2014b) emphasizes, for example, that inequalities reduce growth, by making the poorer individuals less able to invest in education. It contributes also to the wide theoretical literature on inequalities and growth, surveyed in Galor (2011) and Sauer & Zagler (2012). More particularly, this finding is in line with the modern approach of this issue, whose contributions demonstrate that inequalities may be detrimental for economic growth, through their negative effect on human capital formation.

To identify the long-term behaviors of the economy, we analyze the dynamics at the balanced growth paths and we obtain that:

Numerical result 2 (i) *When $\eta > \bar{\eta}(\tau)$, the unique BGP $(k_E, 1, 1)$ is a saddle point, with a stable branch SS_E. (ii) When $\eta < \bar{\eta}(\tau)$, the BGP without inequality $(k_E, 1, 1)$ is stable, while the BGP with inequalities (k_I, x_I^u, x_I^s) is a saddle point with a stable branch SS_I.*

Below SS_j, with $j = I, E$, the economy is stuck in an inequality trap, whereas above SS_j it converges to the BGP without inequality.

The dynamics of the economy in the cases (i) and (ii) can be represented by the Figures 3.1 and 3.2 respectively.[26]

As the threshold $\bar{\eta}(\tau)$ represents the value above which the unstable BGP with inequalities vanishes but also the value above which the BGP without inequality becomes unstable, in the numerical illustration, there always exists an inequality trap, where disparities are constantly widening.

The underlying mechanism behind the coexistence of an inequality trap and a long-term equilibrium without inequality stems from the fact that the return on investment in education varies according to the levels of inequalities and pollution intensity in the economy, as we explained in Section 3.3.2. Indeed, longevity depends on both pollution and individual human capital, which implies that agents have not the same vulnerability to pollution. Consequently, the levels of both pollution and inequalities in human capital lead to a wider dispersion of life expectancy. It means that the period of time during

[26]Note that the second dynamical equation in (3.23), represented by the dashed curve, is discontinuous at $x^u = 1$.

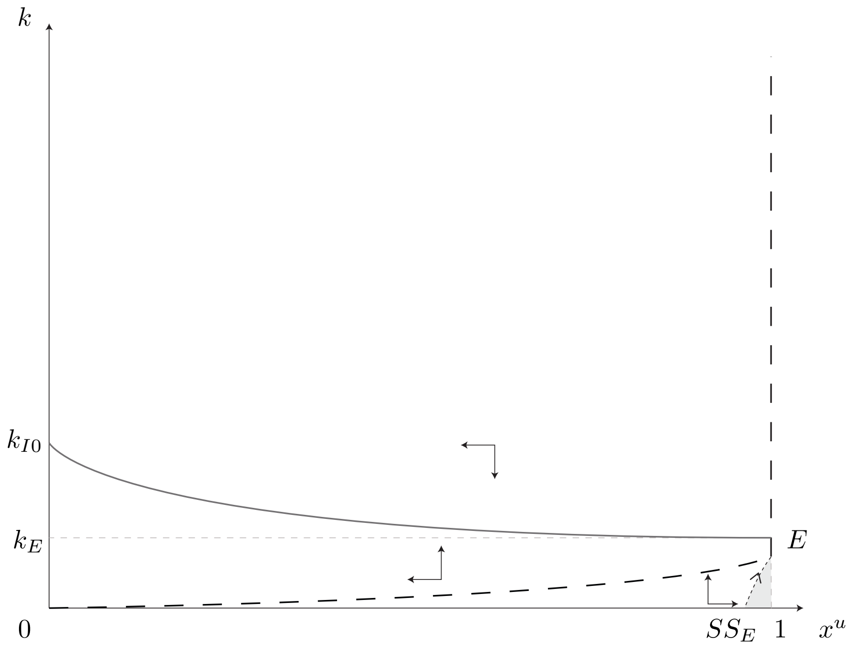


Figure 3.1: Representation of the dynamics of the economy in the case (i)

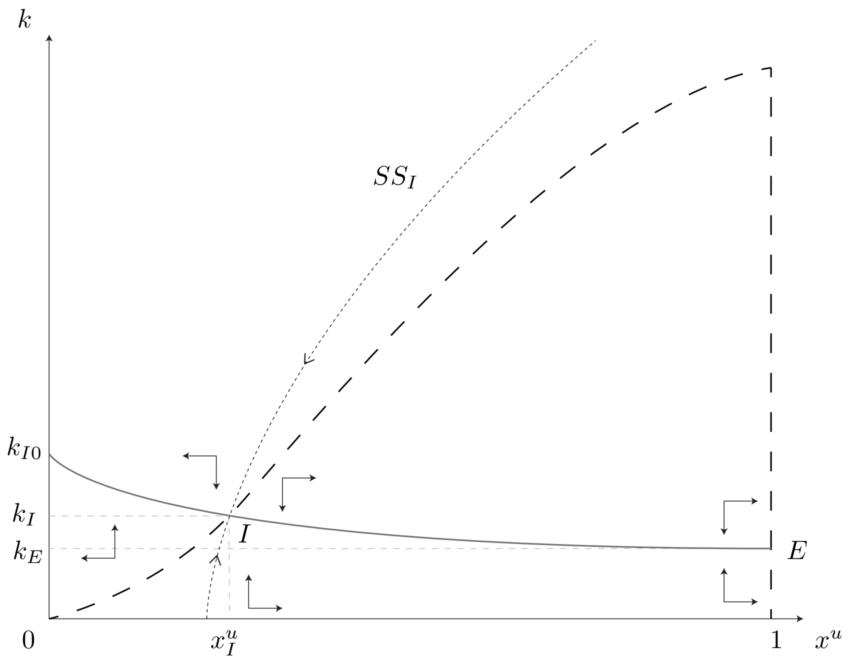


Figure 3.2: Representation of the dynamics of the economy in the case (ii)

which parents can benefit from their investment is very different among agents. Thus their preferences for the future and the return to educate their children are also more unequal. Due to endogenous longevity, the levels of pollution intensity and of inequalities in the economy are crucial in the balance between the convergent force (i.e. average human capital) and the divergent forces (i.e. intergenerational spillover, income dispersion and longetivity dispersion) that drive human capital accumulation.

When the set of initial conditions is such that the economy is above the stable branch SS_j (the dotted curve), the convergent force overcomes the divergent forces, as inequalities are not too wide and the environmental quality is sufficiently high. Therefore, lower-skilled households have a higher return to education investment than higher-skilled households. The growth of individual human capital is larger for the more disadvantaged agents, which allow them to narrow existing disparities over generations and to converge to an equal equilibrium in the long run. Note that this result holds whether the unstable BGP is the one with inequalities I or the one without inequality E. The economy can converge to E even if it is a saddle point when its initial conditions are on the stable branch SS_E but also above it (grey area in Figure 3.1) as the relative human capital of lower-skilled agents x^u is limited by definition to $[0, 1]$. However, it corresponds to very few cases since inequalities and pollution intensity have to be very low (x^u high and k low).

On the contrary, when the initial conditions are below the stable branch SS_j, disparities and/or pollution intensity are initially too large (low x_0^u and high k_0), thus the divergent forces outweigh the convergent force. In this case, the longevity dispersion leads to huge disparities among households education. The return on the investment in education is higher for higher-skilled agents, and the growth of individual human capital is lower for lower-skilled agents. It entails that inequalities are too wide for lower-skilled agents to be able to fill the gap and that the economy is stuck in an inequality trap where inequalities will steadily increase. In particular, when the long-term equilibrium without inequality E is a saddle point ($\eta > \bar{\eta}(\tau)$), the economy is in the trap for most of the initial conditions. Moreover, the higher is the weight of intergenerational transmission in human capital accumulation η, the heavier is the weight of divergent forces and therefore the larger is the size of the inequality trap.[27]

When the economy is in an inequality trap, it converges asymptotically to a state where the level of inequalities is maximum ($k_{I0}, x^u_{I0}, x^s_{I0}$). The human capital of lower-skilled tends to zero ($x^u_{I0} \to 0$), as well as their income and their longevity π^u. Therefore, poor agents die at the end of the second period of life, before retirement. Moreover, they are not able anymore of consuming, saving or educating their children so that the lower-skilled category collapses. On the opposite, higher-skilled households become richer, more educated and live longer. The physical capital to labor ratio and hence the pollution intensity are also higher in this extreme state ($k_{I0} > k_I$). Finally, the long-term growth rate is the lowest at this state $g_{I0} < g_I < g_E$, which confirms that inequalities have a cost in terms of growth. Note that such an extreme case, where the lower-skilled group collapses, is not achieved in reality but it illustrates the constant worsening living conditions of the more disadvantaged households in such a trap.

The study of the long-term behaviors of the economy reveals that the risk to be stuck in an inequality trap, where disparities steadily increase, is important. This result is in line with Castello-Climent & Domenech (2008) who show that an inequality trap can exist due to the transmission of inequalities through life expectancy. Here, we extent their result to the environmental dimension and emphasize that the initial levels of inequalities and pollution in the economy are both crucial to determine if the human capital convergence can occur or not. In particular, the numerical analysis points out that the economy is most likely to be stuck in the trap when the pollution intensity is high, which raises the question of the role that an environmental policy could play in breaking such vicious circle. Therefore, the next section is devoted to the analysis of the

[27]See the sensitivity analysis in Appendix 3.6.5 for more details on the effect of η on the results.

consequences of an environmental policy on the behavior and the growth of the economy in the long run.

3.4 Environmental policy implications

In this section, we assess the effect of a tighter pollution tax associated with an increase in public maintenance on the dynamics and on the growth of the economy. In particular, we want to know whether such an environmental policy can have a redistributive power, as we emphasized the role of pollution intensity in the persistence of inequalities, and whether it can allow to enhance the long-term growth, which is driven by human capital. For each point, we provide, first, an analytical analysis of the implications of the policy, while we illustrate them numerically in a second time.

3.4.1 Environmental policy implications on the balanced growth paths

From Proposition 8, we know that the stability of the long-term equilibrium without inequality depends on the environmental policy, as the tax on pollution intervenes in the threshold determining its stability $\bar{\eta}(\tau)$. Examining how an increase in the pollution tax affects this threshold, we make the following proposition.

Proposition 10 *Under Assumptions 2 and 3 and for $\alpha < 1/2$, the threshold $\bar{\eta}(\tau)$ depends positively on the tax rate τ. Thus, a tighter tax on pollution increases the range of parameters such that the long-term equilibrium without inequality is stable.*

Proof. See Appendix 3.6.3. ■

When the tax on pollution is tighter, it allows the associated investment in environmental maintenance to increase, which reduces the pollution flow. Thus, the longevity of all agents increases, such that their preferences for the future and their investments in education increase too. It implies that the level of human capital is higher. However, although the individual growth of human capital increases for all levels of relative human capital, the decrease in pollution affects relatively more lower-skilled households.[28] Intuitively, even if all agents suffer from the same level of environmental damages, higher-skilled individuals are more able to protect themselves from the negative effect of pollution on health through knowledge, information, or financial means.[29] Thus, public maintenance has a larger effect on the return of investment in education of lower-skilled agents. All agents being proportionally taxed, it follows that an increase in the tax on pollution makes more likely the convergence toward the long-term equilibrium without inequality. Moreover, note that there always exists a sufficient tax rate τ such that the BGP without inequality is stable, i.e. $\eta < \bar{\eta}(\tau)$.[30]

The environmental tax affects also the existence of long-term equilibria with inequalities. The analysis of the threshold $\bar{A}(\tau)$ enables us to identify how it does.

Proposition 11 *Under Assumptions 2 and 3, for* $2\mu + \eta > 1$ *and* $\alpha < 1/2$*, the threshold* $\bar{A}(\tau)$ *depends positively on the tax rate* τ *and the condition* $A < \bar{A}(\tau)$ *is always satisfied when* τ *tends to* 1*. Thus, a tighter tax on pollution increases the range of parameters for which there exists at least one BGP with inequalities.*

A tighter tax makes more likely the existence of one or several balanced growth path(s) with inequalities. However, to be able to conclude on the implications of this proposition on the long-term behavior of the economy, we need to know how many such equilibria are and their dynamics and we cannot evaluate these elements analytically in our model.

[28]More precisely, $\frac{\partial g^i}{\partial \tau} > 0$ but $\frac{\partial^2 g^i}{\partial \tau \partial x^i}$ is > 0 when x^i is small and < 0 when x^i is high, with a threshold equal to $\frac{(a-b\tau)Ak^\alpha(2\mu+\eta-1)}{(1+\sigma(\beta+\gamma\mu))(2-\mu-\eta)}$. Therefore, the increase in the tax reduces this threshold, so that there are more levels of x^i such that lower-skilled are more affected by the increase in environmental quality than higher-skilled.

[29]As Blackburn & Cipriani (2002), we do not formalize health expenditures in this paper (neither private nor public one), but we consider that individual human capital includes the capacity of agents to spend in healthcare. For models with explicit healthcare spending, see e.g. Chakraborty (2004), Pautrel (2008), Varvarigos & Zakaria (2013a) or Raffin & Seegmuller (2014).

[30]This is due to the fact that when the tax on pollution τ tends to 1, the threshold $\bar{\eta}(\tau)$ tends to $1-\mu$, while we assume that $\eta < 1 - \mu$.

That is why we will analyze the implications of the environmental policy on the balanced growth paths and on inequalities in the numerical illustration (Section 3.4.3).

3.4.2 Environmental policy implications on growth

The growth factor of human and physical capital at the balanced growth path without inequality is given by:

$$g_E = \epsilon \left[\frac{\sigma\gamma\mu}{(a - b\tau)Ak_E^{\alpha} + 1 + \sigma(\beta + \gamma\mu)} \right]^{\mu} \tag{3.26}$$

The study of the effect of the environmental policy on this long-term growth rate reveals that:

Proposition 12 *Under Assumptions 2 and 3, a tighter tax on pollution improves the growth rate at the BGP without inequality ($g_E - 1$).*

Proof. See Appendix 3.6.4 ■

Several effects occur. On one hand, a tighter tax on pollution implies a negative income effect. Firms report the pollution tax on the wage rates (w_t) and the returns on savings of households (R_t). On the other hand, a higher tax rate leads to more maintenance activities, which decrease the level of pollution and hence improve health. Through this channel, individuals' longevity enhances, which leads to greater preferences for future motives in the utility function, i.e. savings and children's education. Concerning savings, the negative income effect outweighs the longevity effect, such that savings decrease with a tighter tax on pollution. However, concerning education, a third effect operates. It is important to keep in mind that education is an investment in terms of human capital done by parents and corresponds to an opportunity cost associated with the fact that they do not use this efficient labor to produce, and hence are not paid for that. Therefore, the negative income effect of the tax is neutralized by its positive effect through the reduction of the opportunity cost. Education is thus only affected positively by the environmental policy through longevity. It follows that the stock of human capital improves with the tax. Human capital being the engine of growth in the economy, the long-term growth rate is also enhanced with a tighter environmental policy.

3.4.3 Numerical illustration

We emphasized previously that the environmental policy has severals effect on inequalities and a positive effect on growth at the long-term equilibrium without inequality. In this section, we want to complete the analytical analysis to get a comprehensive overview of the environmental policy implications.

Concerning inequalities, we pointed out in Section 3.4.1 that a tighter environmental policy favors simultaneously the stability of the balanced growth path without inequality and the existence of a balanced growth path with inequalities. With the numerical analysis, we want to illustrate these findings and detail more precisely how the environmental policy affects the long-term behavior of the economy for the parameters considered. Proposition 10 indicates that the tax on pollution increases the value of the threshold $\bar{\eta}(\tau)$. Furthermore, in the numerical illustration, this threshold represents the value under which the long-term equilibrium E is stable but also the value under which the long-term equilibrium with inequalities I exists. In other words, the equilibrium without inequality E becomes stable when the one with inequalities I appears. Thus, it follows that:

Numerical result 3 (i) *When $\eta > \bar{\eta}(0)$, for low levels of the tax on pollution, there exists only the BGP without inequality E which is a saddle point and delimits the inequality trap. However, when the level of the tax becomes sufficiently high, η becomes lower than $\bar{\eta}(\tau)$, which implies that the long-term equilibrium without inequality E becomes stable,*

while the one with inequalities I appears and is a saddle point, delimiting the new trap.[31]
(ii) When $\eta < \bar{\eta}(0)$, the condition such that the BGP without inequality E is stable and the BGP with inequalities I exists as a saddle point is satisfied for all levels of the tax on pollution.

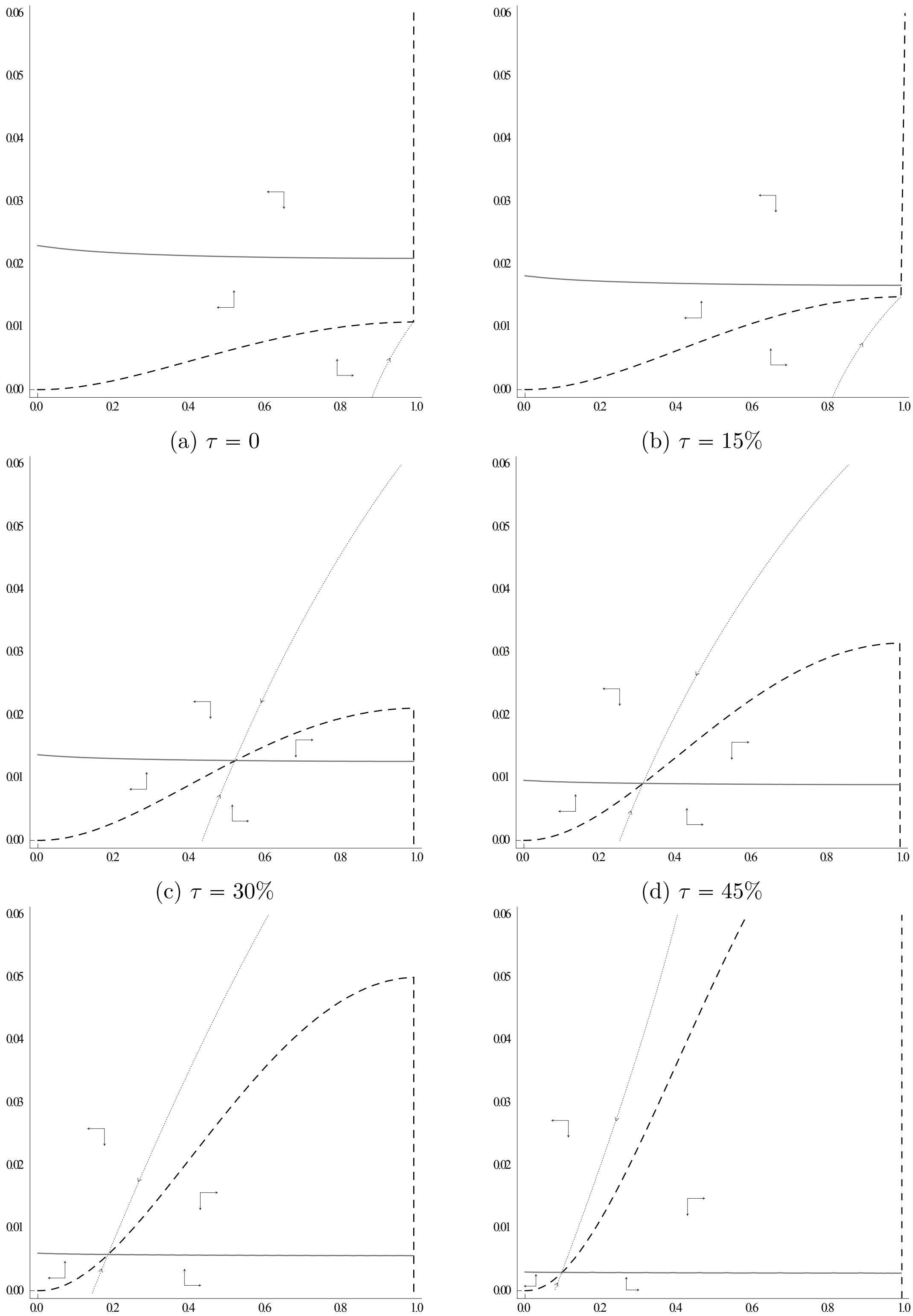
Therefore, we deduce that, when $\eta > \bar{\eta}(0)$, a sufficient tax on pollution allows to reduce the size of the inequality trap, now delimited by the long-term equilibrium I. But beyond this case, we obtain that:

Numerical result 4 *An increase in the environmental tax decreases the size of the inequality trap. Thus, a tighter pollution tax can allow an economy to escape the trap and to converge toward the BGP without inequality.*

By decreasing the size of the trap, a tighter tax may reduce inequalities among households in short run and eradicate them in long run. The mechanism by which environmental policy favors human capital convergence is detailed in Section 3.4.1. To sum up, a tighter tax on pollution enables to reduce environmental damages, which improves the life expectancy of agents and hence their ability to look to the future. In this way, households pay more attention to the education of their children. This effect is even stronger for the more disadvantaged households, who are relatively more sensitive to environmental damages. Consequently, a tighter tax on pollution can allow unequal economies to escape the trap and to reduce disparities along the convergence to a long-term equilibrium without inequality.

To illustrate the Numerical Results 3 and 4, we use the Figure 3.3 corresponding to the case (i) where $\eta > \bar{\eta}(0)$ as it includes the different scenarios. When $\eta > \bar{\eta}(0)$, we have that $\eta > \bar{\eta}(\tau)$ for low values of the tax on pollution, as in the phase diagrams (a) and (b) of the Figure 3.3. Then, the only long-term equilibrium is the one without inequality, but it corresponds to a saddle point and hence delimits an inequality trap in

[31] Note that when τ tends to 1, $\bar{\eta}(\tau)$ is always greater than η.



(a) $\tau = 0$

(b) $\tau = 15\%$

(c) $\tau = 30\%$

(d) $\tau = 45\%$

(e) $\tau = 60\%$

(f) $\tau = 75\%$

Figure 3.3: Phase diagrams when $\eta = 0.35$, i.e. $\eta > \bar{\eta}(0)$, for different tax levels, with x^u on the X-axis and k on the Y-axis.

which the economy is stuck for most of initial conditions. The economy converges to the equilibrium without inequality only if the levels of pollution intensity and inequalities are very low (on the right of the dotted line). When the tax on pollution increases, the inequality trap goes to the left. As one can see in the Figure 3.3, this is due to the fact that the dashed curve, representing the second dynamical equation in (3.25), goes up. Therefore, there are more conditions such that the economy can converge to E. When the tax is sufficiently high (phase diagram (c)), the condition $\eta < \bar{\eta}(\tau)$ is satisfied such that the BGP with inequalities I appears, E becomes stable while I is a saddle. This change implies that the size of the inequality trap reduces and that there are more conditions such that the economy can escape the trap. After that, when the environmental tax continues to increase, the trap continues to decrease, as the BGP I continues to move to the left (phase diagrams (d) to (f)).

As we notice in Section 3.4.1, there always exists a level of the tax such that the economy can escape the trap. However, the more society is unequal and the higher is the pollution intensity before the strengthening of environmental policy, the higher is the tax rate necessary to get out of the inequality trap. In extreme cases, the required tax can be close to 100%. It entails, that for reasonable levels of pollution taxation, the environmental policy may be not sufficient to reduce inequalities. The term reasonable refers to the fact that a tax whose level is too high restricts consumption and hence harms welfare. When the economy is still in the trap after the increase in pollution taxation, it means that inequalities are initially too wide and/or pollution intensity is initially too large to ensure that the improvement in environmental quality is able to overcome the excessive initial disparities on the return on education investment. Thus, inequalities continue to grow.

Consequently, we obtain that an environmental policy, consisting in a public investment in environmental protection financed by a tax on pollution, is an efficient tool to reduce inequalities, through its positive effect on health. Nevertheless, to escape the inequality trap, the government should implement the environmental policy as soon as possible because the later it reacts, the higher is the required level of the tax on pollution.

Our results are related to those of Aloi & Tournemaine (2013) who take into account the effect of environmental policy on inequalities. In their paper, they assume that human capital accumulation of lower-skilled individuals are more affected by pollution than higher-skilled, but this difference depends only on the type of agents and not on their level of human capital. Instead, we extent this mechanism by considering that the effect of pollution on health, and in particular on longevity, is determined by the individual's human capital level, which affects her ability to protect herself through knowledge about pollution or healthy behaviors, through access to healthcare... It follows that the return on investment in education depends on the levels of inequality and pollution in our model and that the economy may be stuck in a trap with widening inequalities or may converge to a long-term equilibrium without inequality. As in Aloi & Tournemaine (2013), the environmental policy leads to a decrease in pollution and favors the more disadvantaged agents. However, in their model, a tighter tax on pollution always decreases inequalities, while it is not always the case for us. The economy may escape the trap following an increase in the tax on pollution when inequalities and pollution intensity are not too high. In this case, inequalities reduce over time until they vanish in the long run. But when these variables are too high, the increase in the tax may be insufficient, which means that the economy continues to be more and more unequal. In this case, other kinds of policy are necessary and can be combine with an environmental policy to favor both education of the less-advantaged agents and the environment, so that the economy can escape the trap. In particular, one can think about an educational policy oriented toward the lower-skilled agents.

Concerning the effects of the environmental policy on the long-term characteristics of the economy, we analyze in the numerical illustration what happens at the two balanced growth paths E and I but also at the limit of the trap $(k_{I0}, 0, x^s_{I0})$, where inequalities are maximum. We observe the following:

Numerical result 5 *A tighter tax* $\tau \in [0, 1)$ *decreases the long-term capital labor ratios* (k_E*,* k_I *and* k_{I0}*) and improves the long-term growth rates (*g_E*,* g_I *and* g_{I0}*).*

We emphasize in Section 3.4.2 that a tighter tax on pollution enhances the long-term growth rate at the balanced growth path without inequality E. The numerical analysis illustrates that it is also the case for an economy still in the inequality trap after the increase in the tax. The mechanism is similar than the one exposed previously. The environmental policy improves the life expectancy of all agents, which enhances their preferences for the future and hence the return on their investment in education. Therefore, the growth rate of average human capital increases. However, in this case, despite the fact that this policy favors more lower-skilled than higher-skilled individuals, it is not sufficient to makes the return to education of lower-skilled larger than the one of higher-skilled parents, so that inequalities in human capital and life expectancy continue to get worse.

Note that, the tax on pollution reduces the flow of pollution in the short run and the pollution intensity in the long run. Nevertheless, we do not know what is the effect on the long-term pollution level, as the size of the pollution depends also on average human capital which grows at the balanced growth path.

3.5 Conclusion

In this paper, we analyze the implications of environmental policy on an economy characterized by health disparities among its population. These inequalities stem from the fact that the life expectancy of an individual depends on the level of pollution in the economy, but also on her level of human capital. Even if everyone suffers from pollution, it is especially a problem for people with low human capital, through the lack of knowledge and information or through difficulties in accessing to healthcare.

We show that multiple balanced growth paths may exist. The economy may converge to a long-term equilibrium without inequality or be stuck in an environmental trap with steadily increasing inequalities. The reason is that endogenous longevity makes the return of the investment in education vary according to the pollution intensity and the level of inequalities in the economy. More precisely, when the levels of inequalities or pollution increase, the life expectancy of lower-skilled agents decreases, which reduces the time they enjoy from their investments and thus their preferences for the future. Moreover, these decreases are in absolute terms but also relatively to higher-skilled agents. Therefore, the gap among households in the economy grows. When the economy is initially not too unequal and not too polluted, education is relatively more profitable for lower-skilled households, so that inequalities can reduce over time and can disappear in the long run. But when initial inequalities or pollution are too high, the return on investment in education may become lower for lower- than higher-skilled households and inequalities among agents persistently grow.

We reveal that an environmental policy, consisting in a tax on pollution and a public investment in pollution abatement, can favor both the development of the economy and the equality among households. First, a tighter environmental policy can allow the economy to escape the inequality trap. The reason is that the improvement in environmental quality increases more the return on investment in education of lower-skilled households, who are more vulnerable to pollution. However, getting out the trap is not always possible for reasonable tax rate. If the levels of inequalities or of pollution are too high initially, the decrease in pollution may be insufficient to outweigh the bad education return for lower-skilled agents. Second, we find that a tighter tax always enhances the long-term growth of the economy. This is due to the positive effect of the decrease in pollution on agents life expectancy which affects behaviors and promotes the investment for the future, as education. We conclude in favor of an environmental policy as a tool to address inequalities and enhance growth. However, it is not always efficient and the government should implement such policy as soon as possible to ensure that inequalities reduce and vanish in the long run.

3.6 Appendix

3.6.1 Proof of Proposition 8

Existence and uniqueness of a BGP without inequality

We study the existence and uniqueness of a BGP without inequality ($x = 1$). When there is no inequality, the dynamics is given by (3.24). At this BGP, we have $k_{t+1} = k_t = k$. We rewrite equation (3.24) as $\Omega_1 = \Omega_2$ with:

$$\Omega_1 \equiv k \frac{(a - b\tau)Ak^\alpha + 1 + \beta\sigma}{(a - b\tau)Ak^\alpha + 1 + \sigma(\beta + \gamma\mu)}$$

and

$$\Omega_2 \equiv \frac{A(1-\tau)(1-\alpha)\beta k^\alpha}{\epsilon(\gamma\mu)^\mu} \left[\frac{\sigma}{(a - b\tau)Ak^\alpha + 1 + \sigma(\beta + \gamma\mu)}\right]^{1-\mu}$$

When $\alpha < \frac{1}{2}$ and under Assumptions 2 and 3, we have:

- Ω_1 is increasing and convex in k, characterized by $\Omega_1(0) = 0$ and $\lim_{k\to+\infty} \Omega_1(k) = +\infty$.

- Ω_2 is increasing and concave in k, with $\Omega_2(0) = 0$ and $\lim_{k\to+\infty} \Omega_2(k) = +\infty$.

Moreover, $\Omega_1'(0) < \Omega_2'(0)$. Thus, the two curves cross only once and there exists a unique positive BGP without inequality $(k_E, 1, 1)$.

The growth factor at the BGP E corresponds to:

$$g_E = \epsilon \left[\frac{\sigma\gamma\mu}{(a - b\tau)Ak_E^\alpha + 1 + \sigma(\beta + \gamma\mu)}\right]^\mu \tag{3.27}$$

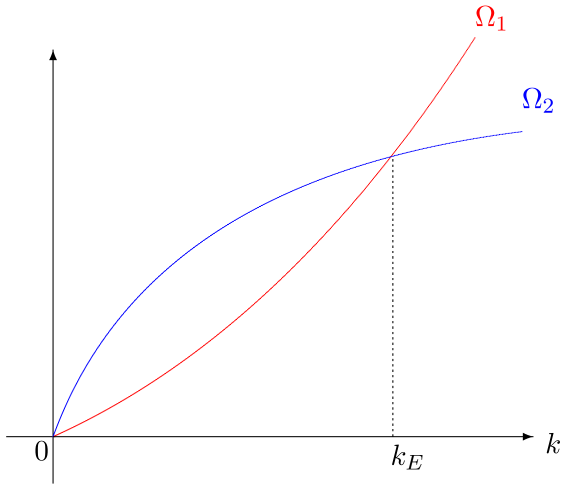


Figure 3.4: BGP without inequality

Thus, the growth rate is positive if $g_E > 1$, i.e.:

$$\epsilon > \left[\frac{(a - b\tau)Ak_E^{\alpha} + 1 + \sigma(\beta + \gamma\mu)}{\sigma\gamma\mu} \right]^{\mu} \equiv \bar{\epsilon} \tag{3.28}$$

Dynamics of the BGP without inequality

To analyze the stability of the BGP without inequality $(k_E, 1, 1)$, we compute the Jacobian matrix associated to the system (3.23) in E:

$$J(k_E, 1, 1) = \begin{pmatrix} \frac{\partial F_1}{\partial k_t}(k_E, 1, 1) & \frac{\partial F_1}{\partial x_t^u}(k_E, 1, 1) \\ \\ \frac{\partial F_2}{\partial k_t}(k_E, 1, 1) & \frac{\partial F_2}{\partial x_t^u}(k_E, 1, 1) \end{pmatrix} \tag{3.29}$$

where F_1 and F_2 are two implicit functions given by the dynamical system (3.23), such that: $k_{t+1} = F_1(k_t, x_t^u)$ and $x_{t+1}^u = F_2(k_t, x_t^u)$. Therefore, we use the implicit function theorem to obtain the elements of the Jacobian matrix.

The partial derivatives of the F_2 at a BGP (k, x^u) are given by:

$$\frac{\partial F_2}{\partial k_t}(k,x^u) = \mu\left(\frac{1-\xi x^u}{1-\xi}\right)^2\left(\frac{(1-\xi)x^u}{1-\xi x^u}\right)^{2\mu+\eta}\left(\frac{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))}{(a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu))}\right)^{\mu-1} \left[\frac{(a-b\tau)A\alpha k^{\alpha-1}(1+\sigma(\beta+\gamma\mu))(x^u-1)}{((a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu)))^2}\right] \tag{3.30}$$

$$\frac{\partial F_2}{\partial x_t^u}(k,x^u) = \left(\frac{(1-\xi)x^u}{1-\xi x^u}\right)^{2\mu+\eta-1}\left(\frac{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))}{(a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu))}\right)^{\mu-1}\left(\frac{(1-\xi x^u)^2}{1-\xi}\right) \left[(2\mu+\eta)\frac{1-\xi}{(1-\xi x^u)^2}\left(\frac{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))}{(a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu))}\right)-\mu\,\frac{x^u}{1-\xi x^u}\,\frac{(1+\sigma(\beta+\gamma\mu))[(a-b\tau)Ak^\alpha+1+\sigma(\beta+\gamma\mu)]}{((a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu)))^2}\right] \tag{3.31}$$

The partial derivatives of the F_1 at a BGP (k, x^u) are given by:

$$\frac{\partial F_1}{\partial k_t}(k,x^u) = \frac{A(1-\tau)(1-\alpha)\beta}{\epsilon(\gamma\mu)^\mu(V_1V_2)^2}\;\frac{\alpha k^{\alpha-1}V_3V_1V_2+k^\alpha\left[V_3'V_1V_2-V_3\left(V_1V_2'+V_2\frac{\partial F_2}{\partial k_t}(k,x^u)W_1\right)\right]}{V_4} \tag{3.32}$$

with

$$V_1 \equiv \xi x^u\frac{(a-b\tau)Ak^\alpha+x^u(1+\sigma\beta)}{(a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu))}+(1-\xi x^u)\frac{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma\beta)}{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))}$$

$$V_2 \equiv \xi\frac{\sigma^\mu(x^u)^{2\mu+\eta}}{((a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu)))^\mu}+(1-\xi)\frac{\sigma^\mu(\frac{1-\xi x^u}{1-\xi})^{2\mu+\eta}}{\left((a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^\mu}$$

$$V_3 \equiv \xi\frac{\sigma(x^u)^2}{(a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu))}+\frac{\sigma\frac{(1-\xi x^u)^2}{1-\xi}}{(a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))}$$

$$V_4 \equiv \quad 1+\frac{A(1-\tau)(1-\alpha)\beta k^\alpha}{\epsilon(\gamma\mu)^\mu}\frac{V_3}{V_2(V_1)^2} \left(\xi x^u\frac{(a-b\tau)A\alpha k^{\alpha-1}\sigma\gamma\mu x^u}{((a-b\tau)Ak^\alpha+x^u(1+\sigma(\beta+\gamma\mu)))^2}+(1-\xi x^u)\frac{(a-b\tau)A\alpha k^{\alpha-1}\sigma\gamma\mu\frac{1-\xi x^u}{1-\xi}}{\left((a-b\tau)Ak^\alpha+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^2}\right)$$

$$W_1 = \xi \Bigg[\frac{(a-b\tau)Ak^{\alpha}+x^u(1+\sigma\beta)}{(a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu))} - \frac{(a-b\tau)Ak^{\alpha}\sigma\gamma\mu x^u}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^2}$$

$$- \frac{(a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma\beta)}{(a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))} + \frac{(a-b\tau)Ak^{\alpha}\sigma\gamma\mu\frac{1-\xi x^u}{1-\xi}}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^2} \Bigg]$$

$$V_2' = -\mu\sigma^{\mu}(a-b\tau)A\alpha k^{\alpha-1} \left[\frac{\xi(x^u)^{2\mu+\eta}}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^{1+\mu}} + \frac{(1-\xi)\left(\frac{1-\xi x^u}{1-\xi}\right)^{2\mu+\eta}}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^{1+\mu}} \right]$$

$$V_3' = -\sigma(a-b\tau)A\alpha k^{\alpha-1} \left[\frac{\xi(x^u)^2}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^2} + \frac{\frac{(1-\xi x^u)^2}{1-\xi}}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^2} \right]$$

and

$$\frac{\partial F_1}{\partial x_t^u}(k, x^u) = \frac{\frac{A(1-\tau)(1-\alpha)k^{\alpha}\beta}{\epsilon(\gamma\mu)^{\mu}(V_1V_2)^2}\left[W_3'V_1V_2 - V_3\left(V_1W_2' + V_2\frac{\partial F_2}{\partial x_t^u}(k, x^u)W_1\right)\right]}{V_4} \tag{3.33}$$

with

$$W_2' = \xi\sigma^{\mu} \Bigg[\frac{(2\mu+\eta)(x^u)^{2\mu+\eta-1}}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^{\mu}} - \frac{(x^u)^{2\mu+\eta}\mu(1+\sigma(\beta+\gamma\mu))}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^{1+\mu}}$$

$$- \frac{(2\mu+\eta)(\frac{1-\xi x^u}{1-\xi})^{2\mu+\eta-1}}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^{\mu}} + \frac{\left(\frac{1-\xi x^u}{1-\xi}\right)^{2\mu+\eta}\mu(1+\sigma(\beta+\gamma\mu))}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^{1+\mu}} \Bigg]$$

$$W_3' = \xi\sigma \left[\frac{2x^u(a-b\tau)Ak^{\alpha}+(x^u)^2(1+\sigma(\beta+\gamma\mu))}{((a-b\tau)Ak^{\alpha}+x^u(1+\sigma(\beta+\gamma\mu)))^2} - \frac{2\frac{1-\xi x^u}{1-\xi}(a-b\tau)Ak^{\alpha}+\left(\frac{1-\xi x^u}{1-\xi}\right)^2(1+\sigma(\beta+\gamma\mu))}{\left((a-b\tau)Ak^{\alpha}+\frac{1-\xi x^u}{1-\xi}(1+\sigma(\beta+\gamma\mu))\right)^2} \right]$$

At the BGP without inequality, $\frac{\partial F_2}{\partial k_t}(k_E, 1) = \frac{\partial F_1}{\partial x_t^u}(k_E, 1) = 0$, while $\frac{\partial F_1}{\partial k_t}(k_E, 1)$ and $\frac{\partial F_2}{\partial x_t^u}(k_E, 1)$ are greater than 0. Therefore, the two eigenvalues are given by: $\frac{\partial F_1}{\partial k_t}(k_E, 1)$ and $\frac{\partial F_2}{\partial x_t^u}(k_E, 1)$. Under Assumptions 2 and 3, under the condition $\alpha < 1/2$, and substituting the expression of k_E given in (3.24) at the BGP $(k_E, 1, 1)$, we have $0 < \frac{\partial F_1}{\partial k_t}(k_E, 1) < 1$.

Thus, the BGP E is stable iif $\frac{\partial F_2}{\partial x_t^u}(k_E, 1) < 1$, which is equivalent to:

$$1 - \left(2\mu + \eta - \frac{\mu(1+\sigma(\beta+\gamma\mu))}{(a-b\tau)Ak_E^\alpha + (1+\sigma(\beta+\gamma\mu))}\right) > 0 \tag{3.34}$$

When the condition given in (3.34) is satisfied, the BGP without inequality is locally stable (a sink), otherwise it is a saddle point. This condition can be rewritten more clearly in terms of η, as $\eta < \bar{\eta}(\tau)$ with

$$\bar{\eta}(\tau) \equiv 1 - \mu \frac{2(a - b\tau)Ak_E^\alpha + (1 + \sigma(\beta + \gamma\mu))}{(a - b\tau)Ak_E^\alpha + (1 + \sigma(\beta + \gamma\mu))} \tag{3.35}$$

Thus, the BGP without inequality E is stable when $\eta < \bar{\eta}(\tau)$ and corresponds to a saddle point when $\eta > \bar{\eta}(\tau)$. Note that when $\mu + \eta \to 0$, the condition (3.34) is always satisfied, i.e. the BGP E is always stable, while when $\mu + \eta \to 1$, (3.34) is never satisfied, i.e. the BGP E is always a saddle.

□

3.6.2 Proof of Proposition 9

We study the existence and uniqueness of a BGP with inequality ($x^u < 1 < x^s$). The dynamical system is described by (3.23) and depends on two variables k and x^u. After computations, the system at the BGP with inequalities, where $x_{t+1}^u = x_t^u = x^u \neq 1$ and $k_{t+1} = k_t = k$, corresponds to:

$$\begin{cases} k^{1-\alpha} \frac{\epsilon(\sigma\gamma\mu)^\mu}{A(1-\tau)(1-\alpha)\beta} \left[\frac{\left[(a-b\tau)Ak^\alpha + \frac{1-\xi x^u}{1-\xi}(1+\sigma\beta)\right]\left[(a-b\tau)Ak^\alpha + x^u(1+\sigma(\beta+\gamma\mu))\right] + \xi x^u (a-b\tau)Ak^\alpha \sigma\gamma\mu\left(\frac{1-\xi x^u}{1-\xi} - x^u\right)}{(a-b\tau)Ak^\alpha\sigma\left(\frac{(1-\xi x^u)^2}{1-\xi} + \xi(x^u)^2\right) + \frac{1-\xi x^u}{1-\xi}\sigma x^u(1+\sigma(\beta+\gamma\mu))} \right] \\ \left[\frac{\xi (x^u)^{2\mu+\eta}}{[(a-b\tau)Ak^\alpha + x^u(1+\sigma(\beta+\gamma\mu))]^\mu} + \frac{(1-\xi)\left(\frac{1-\xi x^u}{1-\xi}\right)^{2\mu+\eta}}{\left[(a-b\tau)Ak^\alpha + \left(\frac{1-\xi x^u}{1-\xi}\right)(1+\sigma(\beta+\gamma\mu))\right]^\mu} \right] - 1 = 0 \equiv \mathcal{A}(k, x^u) \\ k = \left[\frac{1+\sigma(\beta+\gamma\mu)}{(1-\xi)A(a-b\tau)} \frac{(1-\xi)x^u(1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}} - ((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}}(1-\xi x^u)}{((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}} - (1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}}} \right]^{\frac{1}{\alpha}} \equiv \Psi_2(x^u) \end{cases} \tag{3.36}$$

Properties of the function Ψ_2

The second equation of (3.25) defines $k = \Psi_2(x^u)$. Under Assumptions 2 and 3 and the conditions $2\mu + \eta > 1$ and $\alpha < 1/2$, the properties of this function are:

- $Sign(\Psi_2') = u'v - uv'$ with:

$$u = (1-\xi)x^u(1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}} - ((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}}(1-\xi x^u) < 0$$

$$v = ((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}} - (1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}} < 0$$

v' and u' are equal to:

$$v' = \frac{2\mu+\eta-1}{\mu}\left[((1-\xi)x^u)^{\frac{\mu+\eta-1}{\mu}}(1-\xi) + (1-\xi x^u)^{\frac{\mu+\eta-1}{\mu}}\xi\right] > 0$$

$$\begin{aligned} u' &= \xi((1-\xi)x^u)^{\frac{2\mu+\eta-1}{\mu}} + (1-\xi)(1-\xi x^u)^{\frac{2\mu+\eta-1}{\mu}} \\ &\quad -\tfrac{2\mu+\eta-1}{\mu}\left[\xi((1-\xi)x^u)(1-\xi x^u)^{\frac{\mu+\eta-1}{\mu}} + (1-\xi)(1-\xi x^u)((1-\xi)x^u)^{\frac{\mu+\eta-1}{\mu}}\right] \end{aligned}$$

We rewrite this last equation as $u' = \mathcal{I}(x^u) - \mathcal{J}(x^u)$, where $\mathcal{I}(x^u)$ corresponds to the first part (first line) of the equation and $\mathcal{J}(x^u)$ corresponds to the second one.

  - $\mathcal{I}(0) = (1-\xi)$, $\mathcal{I}(1) = (1-\xi)^{\frac{2\mu+\eta-1}{\mu}} > \mathcal{I}(0)$ and $\mathcal{I}'(x^u) > 0$.
  - $\mathcal{J}(0) = +\infty$, $\mathcal{J}(1) = \frac{2\mu+\eta-1}{\mu}(1-\xi)^{\frac{2\mu+\eta-1}{\mu}} < \mathcal{I}(1)$ and

$$\begin{aligned} \mathcal{J}'(x^u) &= \tfrac{2\mu+\eta-1}{\mu}\Big[\xi(1-\xi)\left((1-\xi x^u)^{\frac{\mu+\eta-1}{\mu}} - ((1-\xi)x^u)^{\frac{\mu+\eta-1}{\mu}}\right) \\ &\quad +\tfrac{\mu+\eta-1}{\mu}\left((1-\xi)^2(1-\xi x^u)((1-\xi)x^u)^{\frac{\eta-1}{\mu}} - \xi^2((1-\xi)x^u)(1-\xi x^u)^{\frac{\eta-1}{\mu}}\right)\Big] \end{aligned} \tag{3.37}$$

$\mathcal{J}'(x^u)$ is an increasing function of x^u ($\mathcal{J}''(x^u) > 0$) which is always negative in $x^u = 0$ but may become positive for high x^u when $\xi > 1/2$ ($\mathcal{J}'(1) > 0$ when $\xi > 1/2$).

- u' is negative as long as $\mathcal{J}(x^u) > \mathcal{I}(x^u)$. Thus, we can define a threshold $\hat{x}^u \in (0,1)$ under which u' is negative and above which u' is positive for high level of ξ.

- The condition $u' < 0$ is sufficient to ensure that $\Psi_2' > 0$. Thus, we show that there exists a threshold $\hat{x}^u \in (0,1)$ under which Ψ_2 is an increasing function of x^u and above which Ψ_2 may become decreasing (for high level of ξ).

- Moreover, $\Psi_2 \geqslant 0 \; \forall x^u$, $\Psi_2(0) = 0$ and

$$\lim_{x^u \to 1} \Psi_2(x^u) = \left[\frac{1 + \sigma(\beta + \gamma\mu)}{A(a - b\tau)} \frac{1 - \mu - \eta}{2\mu + \eta - 1} \right]^{\frac{1}{\alpha}} > 0 \tag{3.38}$$

Properties of the function Ψ_1

The first equation of (3.25), $\mathcal{A}(k, x^u) = 0$ allows to define $k = \Psi_1(x^u)$, with $\Psi_1(x^u)$, an implicit function. Under Assumptions 2 and 3 and the conditions $2\mu + \eta > 1$ and $\alpha < 1/2$, we obtain that $\Psi_1(0)$ and $\Psi_1(1)$ are equal to two positive constants.

More precisely, in $x^u = 0$ we have:

$$\begin{aligned} \mathcal{A}(k,0) = 0 &\Leftrightarrow k^{1-\alpha} \tfrac{\epsilon(\sigma\gamma\mu)^{\mu}(1-\xi)^{2-2\mu-\eta}}{A(1-\tau)(1-\alpha)\beta\sigma} \tfrac{(a-b\tau)Ak^{\alpha} + \frac{1}{1-\xi}(1+\sigma\beta)}{\left[(a-b\tau)Ak^{\alpha} + \left(\frac{1}{1-\xi}\right)(1+\sigma(\beta+\gamma\mu))\right]^{\mu}} = 1 \\ &\Leftrightarrow k^{1-\alpha}\left[(a-b\tau)Ak^{\alpha} + \tfrac{1+\sigma\beta}{1-\xi}\right] = \tfrac{A(1-\tau)(1-\alpha)\beta\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}(1-\xi)^{2-2\mu-\eta}}\left[(a-b\tau)Ak^{\alpha} + \tfrac{1+\sigma(\beta+\gamma\mu)}{1-\xi}\right]^{\mu} \end{aligned} \tag{3.39}$$

We analyze the properties of $\Psi_1(0)$ by studying the last equation. For that, we name the function on the left side $f_0(k)$ and the function on the right side $g_0(k)$. Their properties are:

- f_0 is increasing and concave in k, $f_0(0) = 0$ and $\lim_{k \to \infty} f_0(k) = +\infty$.

- g_0 is increasing and concave in k, $g_0(0)$ is equal to a positive constant and $\lim_{k\to\infty} g_0(k) = +\infty$.
- In $k = 0$, $g_0 > f_0$. The two curves have not cross yet, thus $\Psi_1(0) > 0$.
- When $k \to \infty$, we have $\lim_{k\to\infty} f_0 > \lim_{k\to\infty} g_0$. Thus, the two curves cross only once and for a positive and finite value of k.

Therefore, $\Psi_1(0)$ is always a finite and positive constant.

In the same way, in $x^u = 1$ we have:

$$\mathcal{A}(k,1) = 0 \Leftrightarrow k^{1-\alpha} \frac{\epsilon(\sigma\gamma\mu)^{\mu}}{A(1-\tau)(1-\alpha)\beta\sigma} \frac{(a-b\tau)Ak^{\alpha}+1+\sigma\beta}{[(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)]^{\mu}} = 1$$

$$\Leftrightarrow k^{1-\alpha}\left[(a-b\tau)Ak^{\alpha}+1+\sigma\beta\right] = \frac{A(1-\tau)(1-\alpha)\beta\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}\left[(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu} \tag{3.40}$$

As previously, we stydy the properties of $\Psi_1(1)$, by looking at the last equation. We name the function on the left side $f_1(k)$ and the function on the right side $g_1(k)$, whose properties are:

- f_1 is increasing and concave in k, $f_1(0) = 0$ and $\lim_{k\to\infty} f_1(k) = +\infty$.
- g_1 is increasing and concave in k, $g_1(0)$ is equal to a positive constant and $\lim_{k\to\infty} g_1(k) = +\infty$.
- In $k = 0$, $g_1 > f_1$, the two curves have not cross yet thus $\Psi_1(1) > 0$.
- When $k \to \infty$, we have $\lim_{k\to\infty} f_1 > \lim_{k\to\infty} g_1$. Thus, the two curves cross only once and for a positive and finite value of k.

Therefore, $\Psi_1(1)$ is equal to a finite and positive constant.

Comparison of Ψ_1 and Ψ_2

From the study of the properties of Ψ_1 and Ψ_2, we know that $\Psi_1(0) > 0$ and $\Psi_2(0) = 0$, it entails that $\Psi_1(0) > \Psi_2(0)$. It follows that if $\Psi_1(1) < \lim_{x^u \to 1} \Psi_2(x^u)$, there exists at least one BGP with inequalities.

From Appendix 3.6.2, the condition $\Psi_1(1) < \lim_{x^u \to 1} \Psi_2(x^u)$ is equivalent to $f_1(k) > g_1(k)$ in $k = \lim_{x^u \to 1} \Psi_2(x^u)$ given in (3.38). We obtain that $\Psi_1(1) < \lim_{x^u \to 1} \Psi_2(x^u)$ if $A < \bar{A}(\tau)$ with:

$$\bar{A}(\tau) \equiv \left\{ \frac{\epsilon(\gamma\mu)^{\mu}}{(1-\tau)(1-\alpha)\beta\sigma^{1-\mu}} \left[\frac{2\mu+\eta-1}{\mu(1+\sigma(\beta+\gamma\mu))} \right]^{\mu} \left[\frac{1+\sigma(\beta+\gamma\mu)}{(a-b\tau)} \frac{1-\mu-\eta}{2\mu+\eta-1} \right]^{\frac{1-\alpha}{\alpha}} \left[\frac{\sigma\gamma\mu(1-\mu-\eta)+(1+\beta\sigma)\mu}{2\mu+\eta-1} \right] \right\}^{\alpha} \tag{3.41}$$

Thus, under Assumptions 2 and 3 and the conditions $2\mu + \eta > 1$ and $\alpha < 1/2$, the condition $A < \bar{A}(\tau)$ is sufficient so that there exists at least one BGP with inequalities.

Note that when $\mu + \eta \to 0$, Ψ_2 corresponds to strictly negative values of k $\forall x^u$, so that there is no BGP with inequalities in this case.

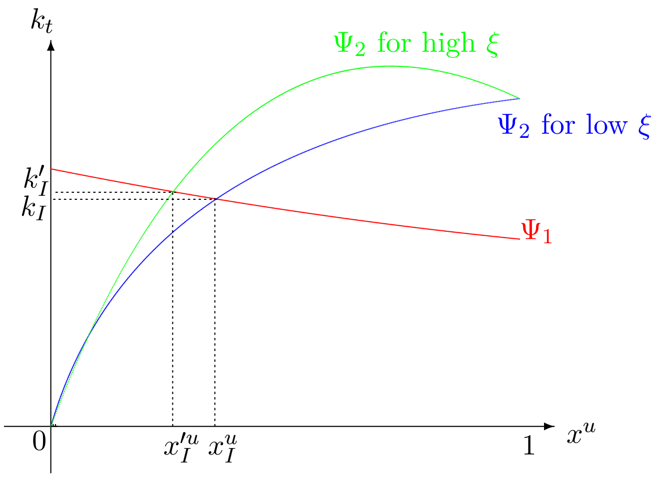


Figure 3.5: A representation of the dynamics when $x^u \neq 1$ (with Ψ_1 decreasing in x^u)

Note that the condition $2\mu + \eta > 1$ does not always imply that the condition $\eta < \bar{\eta}$ of Proposition 1 is not verified. Therefore, it is possible to have these two conditions verified simultaneously, and hence to have both that the BGP with inequalities exists and that the BGP without inequality is stable.

3.6.3 Proof of Proposition 10

The threshold under which the BGP E is stable $\bar{\eta}(\tau)$ is given by (3.35) in Appendix 3.6.1. To analyze the effect of τ on the dynamics of E, we compute $\frac{\partial \bar{\eta}(\tau)}{\partial \tau}$:

$$\frac{\partial \bar{\eta}(\tau)}{\partial \tau} = \frac{\mu(1+\sigma(\beta+\gamma\mu))Ak_E^{\alpha-1}}{[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)]^2}\left(bk_E - (a-b\tau)\alpha\frac{\partial k_E}{\partial \tau}\right) \tag{3.42}$$

The effect of the pollution tax on the dynamics at the BGP E depends on $\frac{\partial k_E}{\partial \tau}$. To compute this derivative, we use the dynamical equation (3.24) at the BGP:

$$\Phi(k,\tau) \equiv k\frac{(a-b\tau)Ak^{\alpha}+1+\beta\sigma}{(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)} - \frac{A(1-\tau)(1-\alpha)\beta k^{\alpha}}{\epsilon(\gamma\mu)^{\mu}}\left[\frac{\sigma}{(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)}\right]^{1-\mu} = 0$$

The effect of τ on k in E is given by the implicit function theorem:

$$\frac{\partial k}{\partial \tau}(k_E, 1) = -\frac{\frac{\partial \Phi}{\partial \tau}}{\frac{\partial \Phi}{\partial k_E}}$$

After computations, we obtain the two partial derivatives:

$$\begin{aligned}\frac{\partial \Phi}{\partial \tau} \quad = \quad & \Big(-bAk^{1+\alpha}\sigma\gamma\mu + \tfrac{A(1-\alpha)\beta k^{\alpha}\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}\left[Ak^{\alpha}(a-b(1-\mu(1-\tau)))+1+\sigma(\beta+\gamma\mu)\right] \\ & [(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)]^{\mu}\Big)\left[(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{-2}\end{aligned} \tag{3.43}$$

$$\frac{\partial \Phi}{\partial k} = \Big[((a-b\tau)Ak^{\alpha})^2 + (a-b\tau)Ak^{\alpha}[2(1+\beta\sigma)+\sigma\gamma\mu(1+\alpha)] + (1+\sigma(\beta+\gamma\mu))(1+\sigma\beta)$$
$$-\frac{A(1-\alpha)(1-\tau)\beta\alpha k^{\alpha-1}\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}\left[(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu}\left[Ak^{\alpha}\mu(a-b\tau)+1+\sigma(\beta+\gamma\mu)\right]\Big]$$
$$\left[(a-b\tau)Ak^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{-2} \tag{3.44}$$

And, we have:

$$Sign\{\frac{\partial \bar{\eta}(\tau)}{\partial \tau}\} = Sign\{bk_E - (a-b\tau)\alpha\frac{\partial k_E}{\partial \tau}\}$$

Thus, $\frac{\partial \bar{\eta}(\tau)}{\partial \tau} > 0$ iif:

$$bk_E\left[((a-b\tau)Ak_E^{\alpha})^2 + (a-b\tau)Ak_E^{\alpha}[2(1+\beta\sigma)+\sigma\gamma\mu(1+\alpha)] + (1+\sigma(\beta+\gamma\mu))(1+\sigma\beta)\right]$$
$$-\frac{A(1-\alpha)(1-\tau)\beta\alpha k_E^{\alpha}\sigma^{1-\mu}b}{\epsilon(\gamma\mu)^{\mu}}\left[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu}\left[Ak_E^{\alpha}\mu(a-b\tau)+1+\sigma(\beta+\gamma\mu)\right]$$
$$+(a-b\tau)\alpha\Big(-bAk_E^{1+\alpha}\sigma\gamma\mu + \frac{A(1-\alpha)\beta k_E^{\alpha}\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}\left[Ak_E^{\alpha}(a-b(1-\mu(1-\tau)))+1+\sigma(\beta+\gamma\mu)\right]$$
$$\left[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu}\Big) > 0 \tag{3.45}$$

It can be rewritten as:

$$bk_E\left[((a-b\tau)Ak_E^{\alpha})^2 + (a-b\tau)Ak_E^{\alpha}[2(1+\beta\sigma)+\sigma\gamma\mu] + (1+\sigma(\beta+\gamma\mu))(1+\sigma\beta)\right]$$
$$+(a-b\tau)\alpha\Big(\frac{A(1-\alpha)\beta k_E^{\alpha}\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}Ak_E^{\alpha}(a-b)\left[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu}\Big)$$
$$+(1+\sigma(\beta+\gamma\mu))\frac{A(1-\alpha)\beta\alpha k_E^{\alpha}\sigma^{1-\mu}}{\epsilon(\gamma\mu)^{\mu}}\left[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)\right]^{\mu}(a-b) > 0 \tag{3.46}$$

Under Assumption 3, the condition $bk_E - (a-b\tau)\alpha\frac{\partial k_E}{\partial \tau} > 0$ is always verified. Therefore, under Assumptions 2 and 3 and for $\alpha < 1/2$, the threshold $\bar{\eta}(\tau)$ depends positively on the tax rate τ.

Moreover, under Assumptions 2 and 3, for $2\mu + \eta > 1$ and $\alpha < 1/2$, the threshold $\bar{A}(\tau)$ depends positively on the tax rate τ and the condition $A < \bar{A}(\tau)$ is always satisfied when τ tends to 1. Thus, a tighter tax on pollution increases the range of parameters for which there exists at least one BGP with inequalities.

□

3.6.4 Proof of Proposition 12

We analyze the effect of the tax rate on the growth factor at the BGP without inequality g_E, given by (3.26). Its derivative with respect to τ is:

$$\frac{\partial g_E}{\partial \tau} = \epsilon(\sigma\gamma\mu)^{\mu}\mu[(a-b\tau)Ak_E^{\alpha}+1+\sigma(\beta+\gamma\mu)]^{-\mu-1}k_E^{\alpha-1}\left\{bAk_E - (a-b\tau)A\alpha\frac{\partial k_E}{\partial \tau}\right\}$$

The effect of the pollution tax on the growth at the BGP E depends on $\frac{\partial k_E}{\partial \tau}$ and more precisely we have:

$$Sign\left\{\frac{\partial g_E}{\partial \tau}\right\} = Sign\left\{bk_E - (a-b\tau)\alpha\frac{\partial k_E}{\partial \tau}\right\}$$

From Appendix 3.6.3, we know that under Assumption 3, $bk_E - (a-b\tau)\alpha\frac{\partial k_E}{\partial \tau} > 0$. Therefore, under Assumption 3, we have that $\frac{\partial g_E}{\partial \tau} > 0$: the growth rate at the BGP without inequality g_E increases following an increase in the pollution tax.

3.6.5 Sensitivity Analysis

In this section, we analyze the robustness of our results with respect to two key parameters: the share of lower-skilled individuals in the economy ξ and the weight of intergenerational transmission in human capital accumulation η. Note that this two sensitivity analysis are done for a particular tax rate τ, i.e. $\tau = 0$ We have performed the analysis for other values and results are similar but to save place, we have only reported here the results for $\tau = 0$. Moreover, we show the impact of the tax on the economy in Table 3.3.

The effect of ξ, representing the repartition of the two types of individuals in the population, is illustrated in Figure 3.6 and Table 3.1. The share of lower-skilled individuals in the population does not affect the value of the long-term equilibrium without inequality but modifies the long-term equilibrium with inequalities. The higher the share of poor individuals in the population, the higher is the capital-labor ratio and the lower is the relative human capital of lower-skilled at the balanced growth path with inequality. It entails that, at this equilibrium, inequalities will be wider and that the growth will be lower. However, the dynamics of both balanced growth paths remains the same. Thus, the threshold in terms of initial inequalities under which the economy is in the inequality trap is lower. The fact that a higher share of population is lower-skilled, for a same average level of human capital, implies that the relative disadvantage of lower-skilled agents with respect to the rest of the population is lower, which makes the human capital convergence easier.

Table 3.1: Sensitivity Analysis with respect to ξ when $\tau = 0$

ξ	k_I	x_I^u	g_I	$CAGR_I$	π_I^u	π_I^s	LE_I^u	LE_I^s	$AverageLE_I$
0.50	0.0241	0.0955	1.5413	1.452%	0.3197	0.8250	69.5919	84.7485	77.1702
0.70	0.0271	0.0738	1.4473	1.240%	0.2615	0.8515	67.8435	85.5435	73.1535
0.90	0.0355	0.0480	1.2439	0.730%	0.1762	0.8818	65.2848	86.4547	67.4018

ξ	k_E	g_E	$CAGR_E$	π_E	LE_E	$Eigenvalues_E$	$Eigenvalues_I$
0.50	0.0209	1.6506	1.684%	0.7724	83.1706	$\{0.911051; 0.318788\}$	$\{1.17236; 0.321711\}$
0.70	0.0209	1.6506	1.684%	0.7724	83.1706	$\{0.911051; 0.318788\}$	$\{1.20855; 0.324857\}$
0.90	0.0209	1.6506	1.684%	0.7724	83.1706	$\{0.911051; 0.318788\}$	$\{1.27981; 0.328051\}$

Notes: $CAGR_j$ represents the compound annual growth rate at the balanced growth path $j = E, I$, while LE_j^i corresponds to the life expectancy in years of the individual i at the BGP j.

Figure 3.7 and Table 3.2 illustrate the evolution of the two long-term equilibria with respect to η, the weight of intergenerational transmission in human capital accumulation.

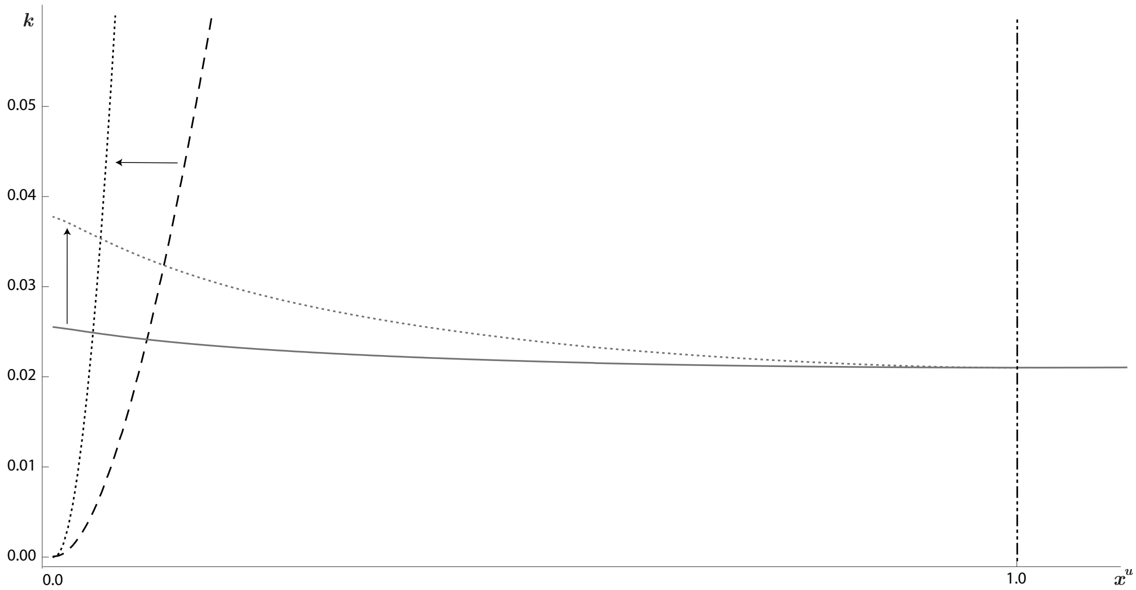


Figure 3.6: Sensitivity analysis with respect to ξ with $\tau = 0$, where the dotted curves capture the case $\xi = 0.9$, while the solid and the dashed curves correspond to $\xi = 0.5$.

As for the share of lower-skilled households in the economy, an increase in the weight of intergenerational spillover has no effect on the values of the variables at balanced growth path without inequality E. On the contrary, at the long-term equilibrium with inequalities, it reduces the capital labor ratio k_I and increases the relative human capital of lower-skilled x_I^u. It entails that the growth rate at the long-term equilibrium I is higher while the level of inequality is lower. Lower-skilled individuals have a higher level of human capital and live longer at this state. As we detail in Numerical Result 2, the dynamics depends on η. For $\eta < \bar{\eta}(\tau)$, the long-term equilibrium without inequality E is stable, while the one with inequalities I is an unstable saddle point.[32] Whereas for $\eta > \bar{\eta}(\tau)$, the unique BGP E is a saddle. Thus, $\bar{\eta}(\tau)$ represents not only the value above which the BGP E becomes unstable but also the value above which the BGP I disappears. The higher is the weight of intergenerational transmission in human capital

[32] $\bar{\eta}(0) = 0.34$ and $\bar{\eta}(1) = 0.4$.

accumulation, the larger is the size of the inequality trap. Indeed, up to the threshold $\bar{\eta}(\tau)$, we have that the higher η, the larger is the size of the inequality trap and the more likely the economy will converge to a situation where the lower-skilled category collapses (see Figure 3.7 and Table 3.2 for some examples). Above this threshold, the economy converges to the equilibrium without inequality only if the initial levels of inequalities and of the capital to labor ratio are very low. Therefore, for most of initial conditions the economy is stuck in an inequality trap.

Table 3.2: Sensitivity Analysis with respect to η when $\tau = 0$

η	k_I	x_I^u	g_I	$CAGR_I$	π_I^u	π_I^s	LE_I^u	LE_I^s	$AverageLE_I$
0.20	0.0259	0.0444	1.4847	1.326%	0.1801	0.8251	65.4019	84.7530	75.0775
0.25	0.0241	0.0955	1.5413	1.452%	0.3197	0.8250	69.5919	84.7485	77.1702
0.30	0.0223	0.2365	1.6010	1.581%	0.5251	0.8213	75.7518	84.6403	80.1960
0.35	∅	∅							
0.39	∅	∅							

η	k_E	g_E	$CAGR_E$	π_E	LE_E	$Eigenvalues_E$	$Eigenvalues_I$
0.20	0.0209	1.6506	1.684%	0.7724	83.1706	{0.861051; 0.318788}	{1.2362; 0.32274}
0.25	0.0209	1.6506	1.684%	0.7724	83.1706	{0.911051; 0.318788}	{1.17236; 0.321711}
0.30	0.0209	1.6506	1.684%	0.7724	83.1706	{0.961051; 0.318788}	{1.08036; 0.320204}
0.35	0.0209	1.6506	1.684%	0.7724	83.1706	{1.01105; 0.318788}	
0.39	0.0209	1.6506	1.684%	0.7724	83.1706	{1.05105; 0.318788}	

Notes: $CAGR_j$ represents the compound annual growth rate at the balanced growth path $j = E, I$, while LE_j^i corresponds to the life expectancy in years of the individual i at the BGP j.

Concerning the effect on environmental policy implications, we obtain that Numerical Results 3, 4 and 5 hold for all the values of the share of lower-skilled households in the population and of the intergenerational spillover.[33] In other words, a sufficient increase in the tax on pollution can allow the economy to escape the “inequality trap". Nevertheless, when the weight of intergenerational transmission of human capital is very high ($\eta > \bar{\eta}(0)$), the effect is a slightly more complicated as the BGP with inequalities does not exist for low values of the pollution tax. We illustrate this case in Table

[33]It is always true considering the calibrated values for the other parameters and for all $\eta \in [0; 1-\mu)$, i.e. the values considered in the model.

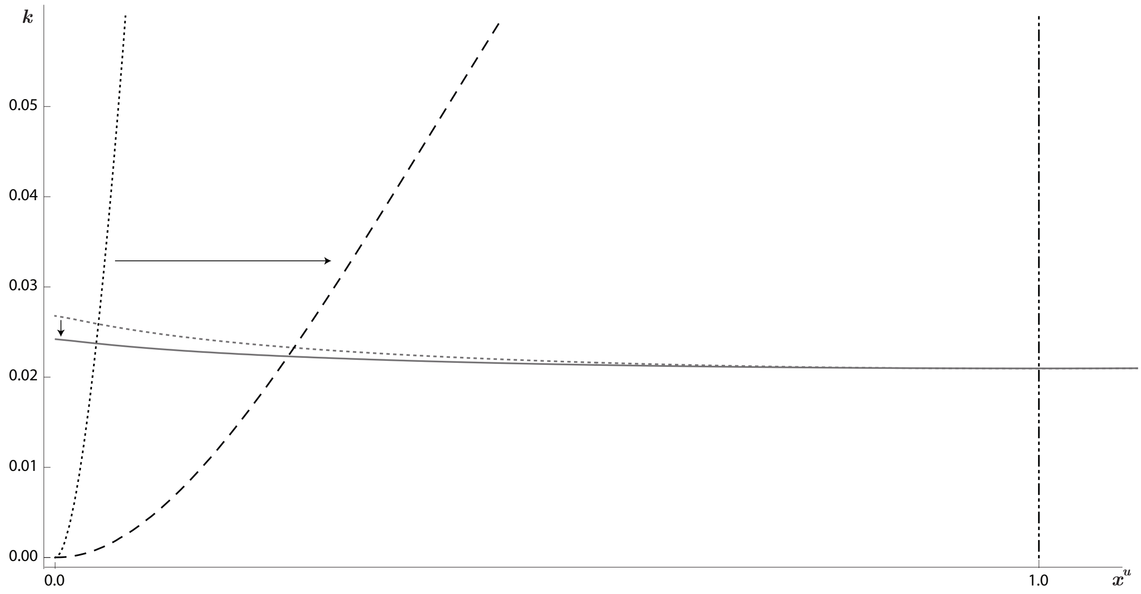


Figure 3.7: Sensitivity analysis with respect to η with $\tau = 0$, where the dotted curves capture the cases $\eta = 0.2$, and the solid and the dashed curves refer to the case $\eta = 0.3$.

3.3. As we have noticed, above the threshold of intergenerational spillover $\bar{\eta}(0)$, the economy is most likely to be stuck in the inequality trap when no environmental policy is implemented or when the tax is too low. As $\bar{\eta}(\tau)$ is increasing in τ, when τ is sufficiently high, η becomes lower than $\bar{\eta}(\tau)$. Thus, the BGP with inequalities appears as a saddle point, while the BGP without inequality becomes stable. In this way, the environmental policy makes that the economy is more likely to converge toward the equilibrium E. For low level of taxation, the size of inequality trap remains very important, but the tighter environmental policy, the more there exist initial conditions such that inequalities among households disappear in the long run. Finally, it should be specified that the required level of tax on pollution for that can be close to 1, when inequalities are initially too wide and/or pollution is initially very high.

Table 3.3: Effect of a tighter environmental policy when $\eta = 0.35$

τ	k_I	x_I^u	$Eigenvalues_I$	g_I	π_I^u	π_I^s
0%	∅	∅				
5%	∅	∅				
10%	∅	∅				
15%	∅	∅				
20%	0.0153	0.7955	$\{1.00255; 0, 32123\}$	1.6714	0.7743	0.8129
25%	0.0140	0.6280	$\{1.00873; 0.322303\}$	1.6730	0.7551	0.8273
30%	0.0127	0.5195	$\{1.01515; 0.323757\}$	1.6746	0.7404	0.8367
35%	0.0115	0.4384	$\{1.02153; 0.323801\}$	1.6761	0.7277	0.8439
40%	0.0099	0.3705	$\{1.02825; 0.333258\}$	1.6784	0.7172	0.8507
45%	0.0091	0.3132	$\{1.03507; 0.325562\}$	1.6793	0.7032	0.8555
50%	0.0079	0.2647	$\{1.04206; 0.326975\}$	1.6809	0.6917	0.8605
τ	k_E	x_E^u	$Eigenvalues_E$	g_E	π_E	
0%	0.0209	1	$\{1.01105; 0.318788\}$	1.6506	0.7724	
5%	0.0195	1	$\{1.00799; 0.318873\}$	1.6562	0.7785	
10%	0.0181	1	$\{1.00493; 0.319171\}$	1.6618	0.7846	
15%	0.0170	1	$\{1.00214; 0.315846\}$	1.6669	0.7903	
20%	0.0153	1	$\{0.998773; 0.320744\}$	1.6730	0.7971	
25%	0.0140	1	$\{0.995776; 0.320691\}$	1.6785	0.8032	
30%	0.0126	1	$\{0.992667; 0.322809\}$	1.6841	0.8096	
35%	0.0113	1	$\{0.989678; 0.323407\}$	1.6895	0.8157	
40%	0.0101	1	$\{0.986708; 0.324157\}$	1.6949	0.8219	
45%	0.0089	1	$\{0.983779; 0.324694\}$	1.7002	0.8279	
50%	0.0078	1	$\{0.98089; 0.325017\}$	1.7054	0.8340	

Notes: The value $\eta = 0.35$ corresponds to the case where $\eta > \bar{\eta}(\tau)$ in $\tau = 0$ and $\eta < 1 - \mu$ (its maximum value in the model).

CHAPTER 4

Conclusion générale

Dans cette thèse, nous nous sommes intéressés à la relation bi-directionnelle qui existe entre la croissance économique et l'environnement. Si l'activité économique peut engendrer des dommages environnementaux très importants, la dégradation de l'environnement affecte en retour l'économie, notamment par le biais des ménages. En effet, la pollution influence le bien-être des individus, leurs préférences, leur santé et donc leurs choix, ce qui peut engendrer des conséquences majeures à court et à long terme pour l'ensemble de la société. Ce travail porte donc une attention particulière aux décisions des ménages, notamment celles guidées par l'altruisme dont les parents font preuve à l'égard de leurs enfants, en termes de legs économiques (d'actifs ou de capital humain) et de legs environnemental. L'objet de cette thèse est alors de compléter la compréhension théorique des interactions entre les sphères économique et environnementale et de prodiguer des recommandations de politiques économiques permettant de diminuer les externalités négatives en découlant.

La relation environnement-croissance présentant un tournant majeur au début du processus d'industrialisation, le premier chapitre est consacré à l'étude des premiers stades de développement. Nous y mettons en exergue le rôle du comportement des consommateurs et de leurs choix au sein de ce processus. L'étude dynamique du modèle nous permet de représenter deux états de long terme : un équilibre pré-industriel correspondant à une trappe à pauvreté, où le développement économique est très faible mais l'environnement est faiblement dégradé, et un équilibre industriel beaucoup plus développé mais également beaucoup plus pollué. L'existence de ces équilibres multiples est due aux interactions des sphères économique, démographique et environnementale. La croissance de la population apparaît alors comme un déterminant majeur du processus d'industrialisation polluante, tandis que la persistance de la pollution est un des éléments responsables de l'existence de la trappe. Ce chapitre nous permet de représenter les grandes disparités en termes de développement observées historiquement. Nous démontrons enfin qu'une économie piégée dans la trappe à pauvreté peut toujours en sortir à l'aide d'un choc technologique suffisamment grand, en accord avec la théorie du *"Big Push"*. Cela illustre le fait qu'aujourd'hui la plupart des pays ont expérimenté un tel processus d'industialisation polluante mais ce à partir de dates très hétérogènes, en fonction notamment de la proximité (géographique ou commerciale) d'une économie avec des pays déjà industrialisés.

Les deux chapitres suivants s'intéressent à la relation croissance-environnement au sein d'économies plus développées. Le deuxième chapitre porte ainsi une attention particulière aux préférences environnementales des ménages, qui déterminent leur volonté de protéger l'environnement. En accord avec la littérature empirique, nous considérons que ces préférences sont endogènes et dépendent du capital humain des individus et de la pollution qu'ils perçoivent, poussant tous deux les agents à prendre conscience de l'étendu du problème environnemental et de ses conséquences. Dans ce cadre, il s'agit d'analyser les implications d'une politique environnementale composée d'outils usuels, tels que la taxe sur la pollution et les dépenses publiques de protection environnementale, et d'un outil éducatif visant à sensibiliser les ménages aux problèmes environnementaux. Bien que n'étant pas un instrument de politique environnementale, l'éducation est très souvent mise en avant par les organisations internationales comme un moyen d'atteindre un développement durable, favorisant à la fois la croissance économique et l'environnement, c'est pourquoi nous voulons étudier son efficacité. Nous montrons qu'une telle politique environnementale peut permettre à la fois d'éviter des inégalités intergénérationnelles, provenant de fluctuations des préférences, mais également de favoriser la croissance de long terme de l'économie. Cependant, pour cela, une allocation appropriée du revenu de la taxe, combinant à la fois dépenses de maintenance environnementale et soutien à l'éducation, doit être mise en place.

Le troisième et dernier chapitre traite des effets de la pollution sur la santé et de l'aspect inégalitaire de leur répartition au sein de la population. De nombreuses études empiriques mettent en évidence l'effet majeur de la pollution sur la mortalité. Mais, face à cet effet, les agents ne s'avèrent pas égaux. Tandis que certains ont les connaissances et les moyens financiers leur permettant de diminuer ces effets négatifs sur leur santé, d'autres en sont dépourvus. Dans ce chapitre, nous considérons les effets de la pollution et du capital humain des individus sur leur espérance de vie, en accord avec les évidences empiriques. Nous révélons qu'il peut exister une trappe à inégalités, où les disparités au sein de la population empirent constamment et que ces inégalités s'avèrent coûteuses en termes de croissance de long-terme. Une économie se retrouve piégée dans cette trappe lorsque les niveaux initiaux d'inégalités et/ou de pollution initiales dans l'économie sont trop élevés. Nous étudions alors les implications d'une politique environnementale, composée d'une taxe sur la pollution et de dépenses de dépollution. Par ses effets sur l'allongement de l'espérance de vie et donc sur le rendement de l'investissement en éducation, il est démontré qu'une telle politique environnementale peut permettre simultanément de diminuer les inégalités au sein de la population et de favoriser la croissance de l'économie. Cependant, elle doit être implémentée avant que les disparités ne deviennent trop grandes. Dans le cas contraire, le niveau de taxe sur la pollution à mettre en place serait trop élevé, ce qui nuirait à la consommation et au bien-être des agents. Aussi, lorsque les disparités sont trop grandes, une politique environnementale ne suffirait pas à atteindre des objectifs environnementaux, économiques et sociaux et devrait être accompagnée d'autres politiques visant directement à diminuer les inégalités, en agissant sur les ménages les plus défavorisés.

Il ressort de cette thèse que les interactions entre le processus de développement et l'environnement entraînent de nombreuses conséquences sur les ménages et sur la société plus généralement, auxquelles nous devons prêter attention. Nous avons notamment pu mettre en évidence que des inégalités peuvent émerger de cette relation, qu'elles soient entre pays, entre générations ou entre membres de chaque génération. Nous montrons aussi le rôle que des politiques environnementales peuvent jouer sur les trois pilliers du développement durable (économique, environnemental et social). En améliorant l'environnement, une politique peut ainsi favoriser le développement économique, notamment par le biais du capital humain, et répondre à des objectifs d'équité sociale. Il semble donc important de continuer à étudier les intéractions réciproques entre ces trois dimensions afin de prodiguer des recommandations politiques les plus complètes possibles.

Parmis les nombreuses pistes de recherches à explorer dans le prolongement de cette thèse, il semble important de tenir compte de la dimension internationale des problèmes environnementaux. Tandis que les pays développés se sont globalement tournés vers des activités faiblement polluantes (de service notamment), les pays en développement se sont au contraire spécialisés dans les activités les plus polluantes liées à l'industrie. Il en résulte qu'à un niveau local, les émissions de pollution de certains pays se sont réduites dans certains pays développés alors qu'elles ont explosé dans les pays en développement. De plus, comme nous l'enseigne la littérature du commerce international, cette spécialisation des activités conduit également à une intensification de la production globale, qui accroît la pollution totale. Les pollutions locales et globales ont des conséquences majeures sur l'économie dont il est important de tenir compte. Tandis que l'environnement local affecte surtout la santé, comme on a pu le prendre en compte dans le chapitre trois, la pollution globale contribue au phénomène de changement climatique. Ce dernier a ensuite des retombées mondiales, notamment via l'accroissement du risque de catastrophes climatiques (ouragan, tsunami, tempête, sécheresse, innondations...) dont découle notamment une grande incertitude sur les niveaux de productions futures. Prendre en compte ces effets pourrait alors permettre de réévaluer les conséquences du commerce international dans la relation unissant développement et environnement. En effet, la dégradation de l'environnement est souvent jugée comme acceptable car compensée par une hausse de la production de chacun des pays, mais ce n'est pas forcément vrai si l'on considère les effets négatifs de la pollution sur l'économie. Une telle analyse pourrait également permettre de réévaluer quelles politiques devraient être implémentées pour atténuer les externalités négatives du commerce international sur l'environnement. Malgré la diminution de sa propre pollution locale, un pays développé pourrait peut-être avoir intérêt à aider l'autre pays à diminuer ses émissions, étant donnés les effets négatifs associés à la pollution globale.

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