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A cooperative differential game of transboundary industrial pollution between two regions

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ABSTRACT

In recent years, the transboundary pollution problems in the world are becoming more and more serious. The diffusion of pollutants is common, and each region which suffers from the pollution wishes that the polluter in neighboring regions would either reduce polluting or compensate for the damages. This paper studies a cooperative differential game of transboundary industrial pollution between two asymmetric regions. There are two novel features in this paper. First, there is a Stackelberg game between the industrial firms and their local government while the governments can cooperate in pollution reduction. Second, transboundary pollution damages the regions in two ways: through a global accumulative pollutant and a regional non-accumulative pollutant. The paper characterizes the parameter spaces that governments in two neighboring regions can collaborate and gives the feedback Nash equilibrium strategies of governments and industrial firms. It is found that only when the governments get cooperation, the regional impact caused by the neighboring region pollution diffusion could be taken into consideration when the governments develop strategies. Additionally, a payment distribution mechanism is proposed and a subgame-consistent cooperative solution is provided. With such a payment distribution, both governments will receive a higher payoff in a cooperative solution than in a noncooperative solution at any instant of time during the game.

1. Introduction

Accompanied with the rapidly increasing population of the world and greater acceleration of economic development in the last century, the pollution problem in the world is becoming more and more serious. As Li (2014) indicated: Pollution in one region can be transported across hundreds and even thousands of kilometers. The incredible distances that pollution can spread means that it is not contained within the boundaries of any single nation. So we call it as "transboundary pollution". This diffusion of pollutants is common and each region which suffers from the pollution wishes that the polluter in neighboring regions would either reduce polluting or compensate for the damages. Our assumption here is that all the participants can come to negotiate it and try to reach an agreement which could be acceptable to all.

Transboundary pollution damages the regions in two ways: through a global accumulative pollutant and a regional non-accumulative pollutant. A classic example of global pollutants is the emission of greenhouse gases which causes global warming. The greenhouse gases (e.g.CO_2, CH_4, et al.) can be maintained in the air for a long time and lead to more floods, droughts, heatwaves, rising sea levels and animal and plant extinctions(Bosello et al., 2003; Bayramoglu, 2006; Bernard et al., 2008). Moreover, in addition to the negative impact from global pollution stock, the non-accumulative pollutants through industrial production emission have regional influence on the surrounding areas. For instance, industrial production processes often emit a mix of pollutants: greenhouse gases and passing-by waste in waterways, wind-driven suspended particles in air; transport activities are typically responsible for emitting a number of pollutants(e.g., CO,CO_2) and volatile compounds (e.g., smog); and the combustion of fossil fuels generates not only greenhouse gases, but also pollutants with more localized effects, such as sulfur dioxide, volatile organic compounds and particulate matter (Yang, 2006; Legras and Zaccour, 2011; Emilson et al., 2009). In the pollutants of these cases, the former

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is hard to get rid of and has an accumulative global impact for the environment (For example, greenhouse gases can contribute to global warming), the latter is a non-accumulative regional pollutant and would affect the neighboring areas (For example, acid rain generated by the industrial activities in one area pollutes the soil of neighboring areas).

As the world gets more pollution, many regional governments have enacted various policies and schemes on reducing pollutants, such as cap-and-trade, pollution tax, etc (He et al., 2014). For the geographical diffusion of pollutants, unilateral response on one region is often ineffective (Ebert and Welsch, 2011). Cooperation in pollution control between two regions is an effective way to reduce pollutants. In many papers, the government is considered as the decision-maker, it determines the output of the region and abatement capital to get a lower emission (Dockner and Nishimura, 1999; Jorgensen and Zaccour, 2007; Breton et al., 2010). But industrial firms are direct consumers of natural resource and the main producers of environmental pollution, so it is necessary to consider their production planning when faced with the governments' pollution tax policy.

This paper studies the transboundary pollution control problem between two regions, characterizes and contrasts non-cooperative and cooperative feedback Nash strategies of two governments and industrial firms. The government in each region can control pollution by adopting pollution tax and setting pollution abatement policy. The industrial firms in each region adjust their own emissions according to the governments' pollution tax policy. Therefore, there is a Stackelberg game between the industrial firms and their government while the two governments cooperate in pollution abatement. Additionally, two types of negative environmental impacts are discussed: The long term accumulative impact on extensive and far-away areas and the short term non-accumulative impact on neighboring areas.

The main purpose of this paper is to characterize the parameter spaces that governments in two neighboring regions can collaborate, and analyze the adjustment of each government's pollution tax policy and abatement policy under the influence of regional and global impacts. It is found that pollution tax rate is affected by the regional damage on source region under non-cooperative game while it is affected by the regional damage on both regions under cooperative game. Then the governments and the industrial firms would not pay attention to regional influence caused by the neighboring region pollution diffusion under non-cooperation. Only when governments get cooperation, the threat posed by the spread of pollution could be taken into account in governments develop strategies. Moreover, a payment distribution mechanism is proposed and a subgame-consistent cooperative solution is provided. With such a payment distribution, both governments will get a higher payoff in the cooperative solution than in the non-cooperative solution at any instant of time during the game.

2. Literature review

In recent years, the transboundary pollution problem in the presence of multiple pollutants has received a large attention in the literatures (Stimming, 1999; Yang, 2006; Luechinge, 2010; Lapan and Shiva, 2011). Caplan and Silva (2005) examine joint tradable permit markets as a self-enforcing mechanism to control correlated externality problems. Multiple pollutants are jointly produced by a single source and the source simultaneously causes differentiated regional and global externalities. They find that joint domestic and international permit markets are Pareto efficient for a wide class of preferences. Legras and Zaccour (2011) propose extending the analysis of intertemporal permit trading to a frame work encompassing multiple correlated pollutants. Moslener and Requate (2009) investigate optimal abatement strategies for cumulative and interacting pollutants. They show that different decay rates can cause non-monotonic behavior in the optimal paths of emissions, the aggregate level of pollution, and even the relative optimal price for emissions. This contrasts strikingly with the case of a single pollutant. In these papers, the types of pollutants are all set to be accumulative. Unlike these literatures, two types of pollutants are set to be an accumulative global pollutant and a non-accumulative regional pollutant in our paper. This is because many regional pollutants are non-accumulative in reality (e.g. the damage of passing-by waste in waterways or acid rain generated by the industrial activities in one area that pollutes the soil of neighboring areas).

Differential game is an effective tool to study pollution control problems and analyze the interactions between the players' strategic behaviors. The dynamic game of transboundary pollution can be found in Petrosyan and Zaccour (2003), Bayramoglu (2006); Jorgensen and Zaccour (2002, 2007), Fredj et al. (2006). Breton et al. (2010) develop a model to analyze how countries join international environmental agreements (IEAs) in a dynamic framework. In the model, where countries suffer from the same environmental damage as a result of the total global emissions, a non-signatory country decides its emissions by maximizing its own welfare, whereas a signatory country decides its emissions by maximizing the aggregate welfare of all signatory countries. And Li (2014) studies the outcome of a pollution game between two neighboring countries, in which emission permits trading is taken into account. These papers do not distinguish the government from the industrial firms in any region. Other references can be found in a survey paper on differential games and environmental problems by Jorgensen et al. (2010). Yeung (2007) and Yeung and Petrosyan (2008) are exceptions, who also analyze the pollution problems considering the industrial firms. But in their model, they assume that the world economy is a form of differentiated products oligopoly with substitute goods. This assumption is certainly limited in reality; pollution should be taken from a variety of types of products. In our paper, we expand this assumption. Diversified products constitute the entire economic system.

Close to our work, Yeung and Petrosyan (2008) also discuss transboundary pollution problem with both global impact and regional negative impact of pollution by a differential game. But for the difficulty of the formula structure, they cannot further analyze the changes of government tax policy and abatement policy under the influence of regional impacts on neighboring areas.

The paper is organized as follows. Section 3 provides the game formulation. Non-cooperative outcomes and cooperative arrangements are characterized in Section 4 and Section 5, respectively. A payment distribution mechanism bringing about the proposed time-consistent solution is obtained in Section 6. A numerical example is provided in Section 7 and concluding remarks are given in Section 8.

3. Game formulation

In this section, a differential game model of environmental management with two asymmetric nations or regions is presented.

3.1. Industrial firm: a Stackelberg game

Consider a global economy comprised of two regions, which are, respectively, denoted by Region 1 and Region 2. There are n industrial firms in Region 1 and m industrial firms in Region 2. The government in each region would control production pollution by adopting pollution tax and it is the leader. The industrial firms in this region adjust their output (emissions) according to the