COOLING THE METROPOLIS: AN ECONOMIC ANALYSIS TO 
ALLEVIATE URBAN HEAT ISLAND 
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August 9, 2007

ABSTRACT. This paper shows the necessary conditions to efficiently combine nongaseous Gorman-Lancasterian characteristics embodied in goods, heat and trace gases as gaseous attributes combined in the urban atmosphere. Sen’s capability approach is used to define personal well-being, since the impacts of urban warming upon each resident affect his/her functionings à la Sen. Any inhabitant or household consumes goods and emits heat and gases in the air. It is demonstrated that any inhabitant maximizes his/her happiness function by consuming goods and emitting heat and gases in the ambient urban air. This paper proposes urban heat island integral to represent the magnitude of heat island and urban warming function. Producers provide goods and landscape gardeners plant trees in residents’ gardens. A tax-subsidy scheme is proposed to cope with urban heat island, which aims to optimally reduce heat in the urban atmosphere.

Key Words: goods as a complex of Gorman-Lancasterian gaseous and nongaseous attributes, heat as an intangible attribute, urban heat island integral, urban heat island tax and subsidy scheme, Sen’s functionings and happiness function

1. INTRODUCTION

1.1. Tokyo is now a gigantic Urban Heat Island with peaks such as Otemachi and Shinjuku which are the central business districts of Tokyo. Whereas, the Imperial Palace, the Meiji Shrine, and the Shinjuku Gyoen National Garden as Cool Islands are cooler, and the temperature of these areas remains rather low compared to the hotter spots mentioned above. By using a concept of Urban Heat Island Integral, formal definitions of a heat island and a cool island are given in Section 2.3.

In the 1930s there were only seven hot nights called tropical nights in which the temperature in the nighttime rose over 25°C. Tokyo had 14 or 15 tropical nights per year in the 1960s. This doubled in the 1990s. We experienced 67 tropical nights in 2000. In 2002, 53 days were observed in which the temperature rose over 30°C. However, this number greatly exceeded that of an ordinary year, i.e., 38.4 days. The average number of tropical nights in Hiroshima City was 4.9 in the 1930s and increased to 28.8 in the 1990s. Kumagaya City in Saitama Prefecture had ten times the amount of days over 30°C than it did just a half-decade ago. The average temperature of Japan hit a new high in November 2003.

The global mean temperature has risen 0.6°C in the past hundred years. It is 0.9°C in Japan and 3°C in Tokyo, thus, Tokyo has been warming more than five times faster than the Earth. The area of Tokyo’s urban district and its artificial emission became one hundred times in the 20th century. Whereas, the increase in the temperature in New York was about 1.6°C in the same period. Tokyo’s urban warming has a remarkable value which is above the rising rate of the past ten thousand years. The Tokyo Metropolitan
Research Institute for Environmental Protection estimated that the heat emitted from cars and air conditioners has resulted in an increase of 0.4°C and that from the loss of greenery by 1.4°C in one hundred years. The green area was halved in Japan from 1930 to 1990, thus, there has been an increase in radiant heat and a decrease in radiational cooling. It is therefore a pressing need to manage the urban heat pollution in the large cities of Japan.

1.2. Different from the results of Rouillon(2000) and (2001) on irreversibility of global warming, urban warming would be reversible within the not so distant future by employing some appropriate countermeasures against urban heat island. As there are some surgical operations for our warming metropolises, some recovery may be expected. We do not have to accept this as an incurable disease. Human beings are unable to have a “zero emission solution,” because they emit heat and CO$_2$ even when breathing and consuming goods. They are also by-products in numerous manufacturing procedures. Hence, we must aim to find a “livable/viable” combination of socially optimal levels of the ambient air quality and heat emissions. The environmental managers of many cities have been utilizing the command and control as well as the tax and subsidy systems. Efficiency of these systems, however, is likely to be lost because they cannot be made cost-effective without exact knowledge of pollution emitted by each household or each firm. Furthermore, if it is impossible to directly observe the amount of each emission, the environmental managers cannot deal with the incentive problem, since relevant information is privately held and must be elicited. Thus, very often, a pollution abatement scheme can be neither informationally efficient nor incentive compatible.

However, heat emitted by each emitter is assumed to be observed somehow or other, so this paper proposes an incentive compatible tax-subsidy system to deal with urban heat island, which can do without the exact knowledge of the heat emitted by each metropolitan agent. Moreover, since urban warming has become a socially significant issue in recent years, increased attention has been paid to scientific breakthroughs and powerful remedies that may be more immediate than economic instruments, such as greening methods and other technological developments to cool down the urban atmosphere.

It has been so far a general case in public economic theory that there is no public good at the beginning of the model, and the issue is how to decide on an optimal quantity of the public good by using the private information, i.e., consumers’ preferences. Our case in the present paper is, however, that the urban atmosphere exists as a public good at the outset, and the problem is how to choose both an acceptable atmospheric quality and a sensory endurable heat emission. Hence, we construct a model to provide an optimal amount of heat as a public good. In order that this model be operational, necessity compels us to devise a tax-subsidy scheme to determine the sum of heat emissions released into the urban atmosphere.

The urban environment should now be perceived to be an intergenerational public good that we have to protect. Metropolitan residents are to be involved in the problem of urban warming which is now confirmed to be caused by heat emissions from human economic activities. Almost all the households living in large cities are polluters as well as victims of the urban warming climate. Metropolitan government is in charge of controlling the total amount of heat emitted by residents and producers to keep the urban climate not so unpleasant in the very near future.

1.3. The ecological system has undergone remarkably changes in metropolitan areas. The cherry-blossom front has changed, i.e., Tokyo could be the first city where the cherry
blossoms bloom in Japan irrespective of its latitude. Tokyo could now be inhabitable for tropical parakeets and hemp palms too. The cicadas have been observed to change from those that like the damp soil to those that are fond of the dry soil, so that intermittent choruses of cicadas have been differing in recent summers of Tokyo. Green-banded swallowtails originally from the torrid zone are protected to propagate in the center of Tokyo with the heat island phenomenon. Palm trees can tune themselves to life in Japan and now winter in the Botanical Garden of Tohoku University in the Sendai city which lies north of Tokyo. Furthermore, something unusual has been happening in the marine ecosystem, i.e., some types of poisonous plankton have increased due to an early outbreak of red tides, which occurred not in July nor August, but in May. The temperature of the surface of brine has increased these past several years.

An incident of heavy rain occurred in Nerima Ward in Tokyo in September 3, 2003. It had 33.9°C and no sea wind. Whereas a sea breeze with a wind velocity of 3 meters per second blew to Otemachi in the midst of Tokyo, where it was 32°C, and littoral Shin-kiba with a breeze of 4m/s had 28.6°C. The mercury touched 33.4°C in Tokyo, but 19mm per 10 minutes of heavy rain from 18:30 to 18:40 decreased its temperature from 31°C to 24.2°C, and it was accompanied by thunder and flashes of lightning. In 2005, Nerima had urban torrential floods possibly due to urban heat island, and approximately seven hundreds of houses were flooded by the rains.

It is reported that Otemachi had more rain than the twenty-one suburban areas: it was 30% more than the other areas at the maximum. The Tokyo Metropolitan Government appointed priority areas where it endeavored to prepare rainpool improvement projects to raise the drainage capacity of the sewers. There is also an increasing possibility that underground shopping centers will be submerged by urban floods possibly due to urban heat island.

Since large cities such as Tokyo, Osaka, Sendai, Hiroshima, Fukuoka, Nagoya, and Sapporo consume an enormous amount of energy by using cars and air conditioners, urban warming has now become notable. Cars have been multiplying unusually in Japan, and the 7 million cars are in circulation every day, which end in huge energy consumption. It follows that there is also an increase in emissions of heat from car air conditioners. One fifth of cars are now RVs that drivers can buy cheaper than before the introduction of an auto tax. A few decades ago, each family owned a car, but now it is more common for each person to possess a car. Thus, the number of drivers has augmented by 24% in this decade.

Heat island remarkably reveals itself in winters, when the temperature does not go under the freezing point. One of the main factors of urban heat island is the alteration of land usage, since the heat stored crucially depends upon what ground covering materials are used. The temperature is higher with concrete covering than with bare and turf grounds, as artificial covering takes in heat. Dryness has been advancing in supercities, because the roads and grounds are paved with asphalt and concrete, which give off heat during the day and take it in at night. Also because of this paving, the water vaporized by the ground has decreased and the reflection of heat is severe in the summertime.

Urban agglomeration has been increasing the number of houses and condominiums, which entails a loss of greenery and water. Factories have been decreasing, but houses have been increasing: half of the 23 wards of Tokyo(60,000ha.) share housing which has augmented by 30%. Heat from houses and buildings has increased to three times as much as three decades ago. It is now far ahead of heat from cars. The diffusion rate of air conditioners was 30% thirty years ago, however, it is over 120% now, i.e., many
households have more than two air conditioners.

1.4. It has been reported that urban heat island has been accelerating air pollution, which has resulted in a dust dome: dust pollution is shut in as if it forms a dome. Photochemical smog occurred for 23 (30, resp.) days in Tokyo (in Saitama Prefecture, resp.). However, the emission of NO\textsubscript{x} was 51,000 tons in Saitama, whereas it was 65,000 tons in Tokyo. This inverse of phenomena could be explained by urban heat island. Hence, countermeasures for tackling the issue of urban heat island have the positive side effect of mitigating urban air pollution. It is observed that urban heat island is closely related to pollinosis or hay fever, and urban air pollution. Enormous pollen was scattered in 2005, i.e., more than 10,000 in square centimeter. It was due to the last summer’s heat wave, and thus an increase of pollen allergy was worried in 2005. However, an analysis of urban heat island’s effects on the local air pollutants is postponed to the future research.

“Integral” and “exponential” are two key adjectives given to the present state of the large cities in peril of urban heat island, e.g., population explosion, build up of noxious nitrogen dioxides due to increasing cars, and decreasing natural green resources. All of these phenomena in the metropolitan areas, which have been induced by human activities, especially agglomeration due to urbanization and motorization share common integral and exponential features, particularly after the drastic economic growth three decades ago. The atmosphere of the supercities has been revealing the similar integral and exponential trends most prominent in these past decades. In order to alleviate the warming tendency in large cities, every economic agent should pay as a user charge of the urban atmospheric air, i.e., a “urban heat island tax,” introduced below.\textsuperscript{1}

Temperature revealed an exponential trend most prominently in recent decades. The atmosphere is a composite of gases such as nitrogen (N\textsubscript{2}), oxygen (O\textsubscript{2}), hydrogen (H\textsubscript{2}), water (H\textsubscript{2}O), and Greenhouse gases (GHGs) such as carbon dioxide (CO\textsubscript{2}), methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), etc. These gases can be considered as gaseous attributes à la Gorman-Lancaster, precisely defined below. The urban atmosphere is made up of 78\% nitrogen, 21\% oxygen, water vapor, trace gases supra, etc.

The floor space of buildings and their energy consumption in Tokyo have considerably augmented in the past century. High-rise buildings are now limited to several areas. However, due to the progress of urbanization and the augmentation of energy intensity of office automation business machines, energy consumption has grown rapidly. As the capacity intensity and floor area ratio increase, the total energy released to the ambient atmosphere grows remarkably. Agreeability of urban life is markedly lost when the temperature exceeds 40°C, when metabolitans would have serious problems of health. Tokyo, with horribly high humidity, will experience such unpleasantness in the near future, as approaching year 2030.\textsuperscript{2}

This paper proposes to consider urban atmosphere as a complex of gaseous attributes, and the goods combined by nongaseous attributes that are produced by the firms, and the green areas as a composite of biological attributes supplied by gardeners. In this paper each resident emits heat and GHGs and has his/her land planted by a gardener. For this, I adopt an analytical framework of the New Consumer Theory by Gorman and Lancaster, and Sen’s Capability Theory.

\textsuperscript{1} See, for example, Hourcade et al.(1997) for an international carbon tax to moderate global warming. See also Henry(1989) for a market of emission rights as an alternative to the tax scheme.

\textsuperscript{2} For simulations of future Tokyo, see, for example, Saitoh, Shimada and Hoshi(1996), Saitoh and Yamada(1999), (2000) and (2001).
The paper proceeds as follows: Section 2 presents the periurban model of regional urban warming in the attributes/functionings framework à la Gorman-Lancaster-Sen and proposes the concept of *Urban Heat Island Integral*. Our model involves residents, offices, hotels, manufacturers and farmhouses such as producers, and gardeners who play a very important role to cool down a metropolis by mural and roof-top gardening and tree-planting activities, etc. Finally there follow some remarks.

2. URBAN HEAT ISLAND IN A PERIURBAN CITY

2.1. *Urban Heat Island Intensity*

Urban heat island is represented by a contour line on a map joining points of equal temperature in the inside and the outside of a city. It is an analogy of a contour line of an island in a sea. *Urban heat Island Intensity* is defined as the highest height of an island.

Let $\tau_u$ and $\tau_r$ be the temperature of the urban and the rural areas of a city. Urban temperature can be represented by $\Delta \tau$ or $(\Delta \tau/\tau_r) \times 100$, where $\tau_u = \tau_r + \Delta \tau$ or $\Delta \tau = \tau_u - \tau_r$. The following notation is also used.

- $\Xi$: heat capacity radiated from the surface to the atmosphere, i.e., sensible heat flux [W/m²];
- $\Pi$: city size [m];
- $\Delta T/\Delta m$: the difference in temperature [°C] between the places vertically separated [°C];
- $Q$: air specific heat [Wh/kg°C];
- $M$: atmospheric density [kg/m³];
- $V$: wind velocity [m/s].

Summers(1965) proposed a procedure to easily calculate heat island intensity, which was further simplified by Takeo Oka as the formula:

$$\Delta \tau = \sqrt{\frac{\Xi \Pi \Delta T/\Delta m}{1800QMV}}.$$  

It has been confirmed that this equation can be adapted to such cities as Lund in Sweden. Oke(1973) also proposed the formula:

$$\Delta \tau = 1.93 \log P - 4.76$$

where $P$ is the population of a city. This function means that population and urban temperature are closely related. He believed that this formula would be applicable to European and North American cities. Park(1987) verified the correlation for Japanese and Korean cities. Yamashita(1988) for heat island in Japanese cities such as Kawagoe City in Saitama Prefecture. Sundborg(1951) was the first to introduce a traveling observation in Uppsala. He statistically verified the difference of temperature among the midtown area and rural points as a function of cloudiness, temperature, absolute humidity, and wind velocity. Duckworth and Sandberg(1954) leapt suddenly to fame by showing the urban high temperature in an aerial photo of San Francisco. It was after their paper that the phenomenon was named “urban heat island” in which there has been a growing interest since then.

Heat Island Intensity for the center of Sendai City in the Tohoku District in Japan will be about 10.5°C, since the temperature is anticipated to increase by 5°C by 2030. The temperature has risen 2.1°C in Sendai in the past hundred years. It is the second highest record next to Tokyo. However, it is reported that the zelcova trees planted in the main streets in Sendai can make a decrease in the sensory temperature of 5°C.\(^3\) Foolishly,
unjust cutting of these irreplaceable zelcova trees is being planned to construct a subway at risk to deficit financing. It must be an unwise behavior from the viewpoint of residents in Sendai. In Tokyo, the center of urban heat island is found in the Nakano or Suginami Wards in winter time and heat island intensity is $3^\circ C$. It is 10~15km in diameter and its form is the same all day long.

2.2. A Model of Heat Island in a Periurban City

This section introduces the Characteristics/Functionings model based on the Gorman-Lancasterian theory where goods are regarded as a composition of characteristics. For the sake of simplicity, the two terms, “attributes” and “characteristics,” are used interchangeably throughout this paper. All trace gases such as GHGs can be interpreted as *intangible gaseous attributes* in our framework, since they partially compose the urban atmosphere as an urban public good. Characteristics of urban climate are in order: pollution substances, solar radiation, cloudiness, precipitation, temperature, absolute and relative humidity, and wind velocity. These attributes compose the urban ambient atmosphere. This paper focuses upon heat as an attribute, since it is the main cause of urban warming. Before rushing into our theoretical model, let me introduce some basic concepts of urban heat island.

Let us consider a monocentric periurban city which is supposed to be a “climatically closed city,” i.e., there are no climatic influences from and on the neighboring cities. “Periurban” means the peripheral zone of the urban area, where reside inhabitants, manufacturers, farmhouses and gardeners. For the sake of simplicity, assume that our periurban city is composed of two areas, i.e., the urban area and the periurban area, which are divided into many blocks, $\beta \in \beta = \{1, ..., B\}$: the set of blocks. In other words, our periurban city is represented by a mesh of blocks, such as a grid of the center of Chicago. Assume that whatever size and shape can be chosen for a block, as a smaller size in Tokyo or a larger one in Chicago.

Let there be $N$ residents indexed by $i \in N = \{1, ..., N\}$: the set of inhabitants who live in the periurban belt. Residents could be households. Each individual emits heat and trace gases when consuming goods or services indexed by $j$ and its set is $J = \{1, ..., J\}$. For the sake of simplicity, it is assumed that each producer $j$ supplies only one good $j$ which is composed of $C$ characteristics indexed by $c \in C = \{1, ..., C\}$: the set of attributes. Denote as $q_{jc}$ an amount of attribute $c$ embodied in one unit of good $j$. There are three categories of producers: i.e., offices, manufacturers, and farmhouses.

Suppose that resident $i$ chooses a gardener named $\ell$ to have a part of his/her land planted with trees and flowers, and $A = \{1, ..., A\}$ is the set of gardeners. Define $q_{fs}$ as a biomass of species $s$ in one square meter supplied by gardener $\ell$, and $S = \{1, ..., S\}$ as the set of species of flora and fauna as *biological attributes*. Let $x_{ij}$ be resident $i$’s consumption of good $j$, and $A_{\ell i}$ be his/her demand for the green area supplied by gardener $\ell$, then, $x_i = (x_{i1}, ..., x_{ij}, A_{\ell i})$ is his/her consumption vector. There is also the metropolitan government whose task is to reduce heat emission by making effective use of an *urban heat island tax/subsidy scheme* defined below. Not to mention, every inhabitant, producer or gardener resides in some block, so that an index $\beta$ will be omitted hereafter in almost all the cases, except for describing some variables related to block $\beta$.

Different from von Thünen(1826), or usual urban economic theory, it is hypothesized that our periurban city as follows:

H1. The city is formed in a heterogeneous plain, where the climate could differ among its blocks.
H2. The city is not necessarily circular and its center is called the Central Business District (CBD).
H3. Its urban and periurban transportation systems are available in whatever direction.
H4. Land in the city is all owned by absentee landlords.
H5. All periurban residents commute to work for an office in the CBD, work in a manufacture or for a farmhouse.
H6. All gardeners plant areas in a part of lands of residents in the periurban zone.
H7. Manufacturers produce goods and farmhouses make agricultural products in the periurban region.

The urban atmosphere is regarded as a complex of gaseous attributes including trace gases, which are to be mainly generated by production and consumption activities. It is naturally assumed that the amount of gases such as \( \text{N}_2, \text{O}_2, \text{H}_2 \) are stationary, so I can focus upon heat and trace gases as intangible attributes in this paper. An index \( q_{jg} \) is also used hereafter to identify the \( g \)th gaseous attribute, and \( q_{jH} \) is an amount emitted of heat as an attribute when producing one unit of good \( j \). Let \( G = \{ C + 1, \ldots, C + G \} \) be the set of trace gases which compose the urban atmosphere.

Taking urban warming into consideration, let us extend and generalize the framework developed by Sato (2006a). When producing one unit of good, each producer does not choose but to jointly emit heat and trace gases as vexing by-products, \( q_{jh} \geq 0 \), which is producer \( j \)'s unit emission of heat or each gas. Thus, \( q_{jhx_j} \) is producer \( j \)'s amount emitted of heat when it produces \( x_j \) units of good \( j \). Gardeners also emit heat and gases, \( q_{gh} \geq 0 \) and \( q_{gA} \geq 0, \forall g \in G \), which are gardener \( \ell \)'s unit emission of heat and any gas. Hence, \( q_{gA}A_\ell \) and \( q_{gh}A_\ell \) are gardener \( \ell \)'s emitted quantity of a gas or heat in his/her production of \( A_\ell \) units of greening service \( \ell \). Inhabitants also emit heat and gases, \( q_{ih} \geq 0 \) and \( q_{ig} \geq 0, \forall g \in G \), which is city dweller \( i \)'s unit emission of heat and gas. Hence, \( q_{ih}A_i \) and \( q_{ig}A_i, \forall g \in G \), is individual \( i \)'s emitted quantity of a heat and gas in his/her consumption of \( A_i \) units of greening service \( \ell \).

Let \( z_{i0} \) be resident \( i \)'s numéraire characteristic that he/she possesses, by which other attributes can be utilized. Amounts of each attribute embodied in the goods and the atmosphere which are consumed by resident \( i \) are given for any \( c \in C \) and for any \( g \in G \)

\[
z_{ic} = \sum_{j \in J} q_{jc}x_{ij} \tag{1}
\]

\[
z_g = \sum_{j \in J} \sum_{i \in N} q_{jg}x_{ij} + \sum_{j \in J} q_{jg}A_j + \sum_{\ell \in \Lambda} q_{\ell g}A_{\ell \ell} + \sum_{i \in N} \sum_{\ell \in \Lambda} q_{\ell g}A_{\ell i} \tag{2}
\]

and

\[
z_h = \sum_{j \in J} \sum_{i \in N} q_{jh}x_{ij} + \sum_{j \in J} q_{jh}A_j + \sum_{\ell \in \Lambda} q_{\ell h}A_{\ell \ell} + \sum_{i \in N} \sum_{\ell \in \Lambda} q_{\ell h}A_{\ell i} \tag{3}
\]

In the above equation, \( z_{ic} \) means the consumption of tangible nongaseous attributes which compose goods, while \( z_g \) and \( z_h \) represents the total amount of a trace gas and heat...
emitted by all residents, producers and gardeners. Note that the values of $z_g, \forall g \in \mathbf{G}$, and $z_h$ can be measured via ton or kilojoule. Heat and gases are generated both in the consumption and production of goods. Every inhabitant is made to consume not only his/her emission but also the quantity emitted by the rest of the city. When he/she uses goods, he/she emits heat and gases which were already released when the goods were made by producers. For the later use,

Both of the above equations may be interpreted as characteristics availability functions, which convert commodities into attributes. The amount of any characteristic in each good can be regarded as a parameter that is objective and common to all consumers, i.e., it has a public-good property. Thus, the inhabitants as consumers must behave as “quality takers”, since they can only change their consumption of $z_{ic}, z_{ih}$ and $z_{ig}$, via the choice of $x_{ij}$ and $A_{it}$. Producers and gardeners can choose the composition of attributes embedded in their goods and their greening service.

A part, $\eta_g z_g, 0 < \eta_g < 1$, of an aggregate emission of gases is observed to stay in the urban atmosphere and the rest, $(1 - \eta_g) z_g$, is perceived to disintegrate. Of this amount, about 46\% of CO$_2$ emission is absorbed by the oceans and forests as carbon sinks. An integration rate or an inverse of a lifetime of each trace gas is denoted as $\lambda_g$, with $0 < \lambda_g < 1, \forall g \in \mathbf{G}$, so that the mass of the $g$th gas that stays in the urban air $(\eta_g - \lambda_g) z_g, \forall g \in \mathbf{G}$.

Allowing $\theta_g$ be a conversion parameter from mass(ton/year) to concentration(ppmv), and $z_g(\gamma)$ be an amount emitted at time $\gamma$ of the $g$th trace gas, then an amount of trace gas accumulated from time $t_0$ to time $t$, which is converted into a concentration is given by

$$
\zeta_g^t = \int_{t_0}^{t} \theta_g (\eta_g - \lambda_g) z_g(\gamma) \, d\gamma, \, \forall g \in \mathbf{G}.
$$

This can be written as

$$
\zeta_g^t = \int_{t_0}^{t} \Theta_g z_g(\gamma) \, d\gamma, \, \forall g \in \mathbf{G}
$$

where $\Theta_g^t \equiv \theta_g (\eta_g - \lambda_g)$ is a climatical parameter related to the $g$th trace gas. An argument of time $t$ is omitted hereafter, unless necessary. Therefore one observes

$$
\mathbf{Z} = (\zeta_1, ..., \zeta_G)
$$

which affects all residents, producers and gardeners in the periurban city, since urban heat island is due to an artificial heat emission and heat storage on the ground coverage in the city.

Another equation is proposed for heat as a flow in the next subsection. It is the microclimate in the block, which most influences any economic agent who resides or works in $\beta$. However, climatical incidents depend upon not only the concentrations in each block, but also those in the entire metropolis, as exemplified in the Nerima incident in the Introduction. The causes of urban torrentail floods were not due to Nerima.

2.3. Urban Heat Island Integral

The problem of how to represent the heat in the city was analyzed in Sato(2006) who introduced the concept of Urban Heat Island Integral. In effect, there must be differences
in the temperature of building surface, back alleys, rooftops, streets, and green tracts of land, which are directly exposed to the solar radiation. However, these differences of the surface temperature of the ground coverage can be measured by utilizing infrared cameras.

Let $A_\beta$ be an area of a block $\beta$ and $S_\beta$ be its level surface projection, i.e., the area which could absorb the solar radiation. More precisely, it is the sum of developable areas of the ground coverage, e.g., the streets, the tree crowns, the rooftops and walls of the buildings, which exist in $A_\beta$. Denote $\tau_\beta(u, w)$ as a function of the surface temperature of $S_\beta$ and $\alpha_\beta(u, w)$ as a function of atmospheric temperature in $A_\beta$, where $u$ and $w$ are the plane coordinates. Then, the Riemann sum led me to propose a concept of Urban Heat Island Integral which reads

$$\UHI = \frac{1}{S_\beta} \left\{ \int_{S_\beta} \tau_\beta(u, w) \, dudw - \int_{A_\beta} \alpha_\beta(u, w) \, dudw \right\}$$

Needless to say, the existence condition of this multiple integral is that the functions, $\tau_\beta(u, w)$ and $\alpha_\beta(u, w)$, are continuous and compact in the domains $S_\beta$ and $A_\beta$, and it is easily seen that this condition is satisfied.

Remark 1. $\UHI$ is not the result of heat emission on the part of the economic agents, but it stems from the ground coverage of the metropolis. $\UHI$ measures the force of urban heat island in each block $\beta$, i.e., the sum of the heat flux from all the surface divided by its area. The temperature of asphalt and concrete is very often higher than that of the atmosphere. It is observed that asphalt and concrete absorb 90% of the solar radiation, so that the walls of buildings made of concrete absorb the same amount of heat, which result in urban warming. Let me give numerical examples of the values in $\UHI$. The mercury stood at 27.5 degrees at an observation point in Shinjuku at 14:00 on June 6, 2002, where the wall of a building made of concrete was observed to have the heat of 38°C and a street of asphalt had 45°C. The central area of Shinjuku ($A_\beta = 4km^2$) must be extended to its plane of projection ($S_\beta = 9.3km^2$), which is exposed to the solar radiation. Also, heat is emitted from the underground shopping center in Shinjuku.

The following formula is physically supposed: Sensible Heat Flux($\varepsilon_\beta$) = Urban Heat Island Integral($\UHI$) × Convective Heat Conductivity($\kappa$), $\forall \beta \in \beta$, where $\kappa$ varies according to the temperature. Block $\beta$ is called a Heat Island if $\UHI > 0$, $\forall \beta \in \beta$, and a Cool Island if $\UHI \leq 0$, $\forall \beta \in \beta$. As was mentioned in the Introduction, the Imperial Palace, the Meiji Shrine, and the Shinjuku Gyoen National Garden as cool islands are cooler than the center of Shinjuku, i.e., the heat flux of the latter was observed to be about 300W/m², whereas it was less than 200W/m² in the Shinjuku Gyoen National Garden by the measurement of the Ministry of Environment. Furthermore, by its observation, rivers in Tokyo are much cooler than the above areas.

Let $\varepsilon_i$, $\varepsilon_j$, and $\varepsilon_\ell$ be heat emitted by resident $i$, producer $j$, and gardener $\ell$ in the city. Denote $\varepsilon_h = \sum_{i \in N} \varepsilon_i + \sum_{j \in J} \varepsilon_j + \sum_{\ell \in A} \varepsilon_\ell$. Total heat emission $E$ which affects all economic agents in the city is thus represented as

$$E(A, W) = \sum_{i \in N} \varepsilon_i + \sum_{j \in J} \varepsilon_j + \sum_{\ell \in A} \varepsilon_\ell + \sum_{\beta \in \beta} \varepsilon_\beta(A, W). \quad (7)$$

The first three terms represent artificial emissions of heat and the last term is the sensible
heat flux generated from the ground coverage, all of which are assumed here to depend upon the amounts of vegetation and water.

A differentiability assumption is posed on the above equation.

**Assumption 1.** (i) $E$ is strictly quasi-concave and twice continuously differentiable with $\partial E/\partial A < 0$ and $\partial E/\partial W < 0$. (ii) $\varepsilon_i, \varepsilon_j, \varepsilon_\ell$, and $\varepsilon_\beta$ are strictly quasi-concave and twice continuously differentiable with $\partial \varepsilon_e/\partial A < 0$ and $\partial \varepsilon_e/\partial W < 0, \forall e = i, j, \ell, \beta$. Moreover, $\partial^2 E/\partial W^2 < 0$ and $\partial^2 E/\partial A^2 < 0$.

### 2.4. Vegetation, Water and the Urban Warming Function

Let $L_i, L_j$, and $L_\ell$ be the land leased by resident $i$, producer $j$, and gardener $\ell$. Also let $A_i \equiv \rho_i L_i$ and $A_j \equiv \rho_j L_j$ be greening areas of their land required to be planted with trees, where $\rho_i$ and $\rho_j$ are greening rates for city dweller $i$ and firm $j$, which are legally determined, e.g., at least 20% of the rooftop on the houses and buildings, when they are newly built, enlarged or reconstructed in Tokyo. Suppose that gardeners are exempted from the obligation of greening a part of their own lands in this model.

As I assumed that inhabitant $i$ chooses one gardener $\ell$ to green a part of his/her land $A_i$ with plants, at a cost of $q_\ell A_i$. Then, each person is to have his/her green area planted with plants, insects and microorganisms in the soil. These living things are regarded as biological attributes that may be offered by gardener $\ell$ as by-products, and let $A_{i\ell}$ be his/her area $A_i$ planted by gardener $\ell$. City dweller $i$ therefore consumes biological attributes by possessing the green area in his/her land as represented by

$$z_{is} = q_{is} A_{i\ell}, \forall s \in S, \forall \ell \in \Lambda.$$  \hspace{1cm} (8)

Resident $i$ can enjoy seeing creatures in his/her green area: they may be trees, flowers, insects, birds, or minute animals.

Suppose that each producer has an environmental branch which is in charge of planting trees in a part of its lot size $A_j$ with its cost $\sigma_j$. Let $A_P = \sum_{\beta \in \beta} A_\beta$ be the area to be planted with street trees and tree lawns undertaken by public works, and $\Gamma(A_P)$ is its cost. Summing these green areas yields

$$A = \sum_{i \in N} \sum_{\ell \in \Lambda} A_{i\ell} + \sum_{j \in J} A_j + \sum_{\beta \in \beta} A_\beta.$$  \hspace{1cm} (9)

Incidentally, passers-by can see hedges of others’ houses, and can have beautiful views of parks. Children can amuse themselves in small parks which would stud the cities to and fro. These green areas are regarded as amenities, which may be clubs or excludable public goods.

The quantity of water existing in the metropolis is crucially important to cool supercities, thus, underdrained rivers must be resuscitated. Let $W$ be the total amount of water in the metropolis represented by

$$W = W_0 + W_P$$  \hspace{1cm} (10)

where $W_0$ is the quantity of water that already exists and $W_P$ is the amount which is to be revived by public enterprises with a cost $\Omega(W_P)$, e.g., resuscitating culverts.

By Physics, it is easily concluded that the more abundant the amounts of $A$ and $W$, the cooler the metropolis, i.e., the more, the better. Notice that $A$ and $W$ have a
public-good property, since their cooling effects can prevail all the blocks of the metropolis as beneficial externalities. The sum of green area $A$ is composed by plants and other living things as biological attributes. $A$ and $W$ not only cool down cities, but also give residents a tasteful life instead of a prosaic life, so that they enter in city dweller $i$’s consumption vector of attributes as public goods. This paper focuses on greening as one of the important natural factors which plays a significant role in cooling down the supercity. Modeling the water management in more detail is presented in Sato(2006b).

Sensible heat flux from the ground coverage of the metropolis therefore is represented by

$$\sum_{\beta \in \beta} \varepsilon_{\beta}(A, W) = \kappa \sum_{\beta \in \beta} \Upsilon_{\beta}. \quad (11)$$

Note that this function depends on the planted areas and the amount of water. Both of them can diminish the value of $\Upsilon_{\beta}$ by cooling down the ground coverage of the city.

Total heat emission defines the Urban Warming Function:

$$U = U(E). \quad (12)$$

Denote $E = N \cup J \cup A$. The following assumption is needed.

Assumption 2. $U$ is strictly quasi-concave and twice continuously differentiable with $\partial U/\partial e > 0$, $\partial^2 U/\partial e^2 > 0, \forall e \in E$.

Remark 2. Urban warming is a typical example of a public good which is both nonrival and nonexcludable. However, its impact on each resident varies from region to region, which can be treated as a regional public good. Urban heat island with 33.5°C occurred in some blocks of the Nerima Ward, Tokyo on July 21, 1999, which was not necessarily due to the consumptions and productions of goods in that area, but due to those of the rest in Tokyo, as well as the climate conditions of the block at that time. Consequently, the worst that could happen to any block where some climatic conditions are satisfied at some point in time, as in the above unforeseen incident. The function $U$ therefore depends mainly upon the total heat emission $E$ in the urban atmosphere. The analysis in this paper therefore proceeds on the premise that the urban heat island is primarily attributable to the factitious heat emission and natural heat storage at the ground coverage of the city.

Urban warming may now be regarded as a negative externality which has been directly provided by the human activities of economic agents who emit heat into the urban air. Its climate damages can be measured in physical units, which are, in order: i) an increase in heat strokes due to temperature rises, ii) an increase in the occurrence of showers and localized torrential downpours, iii) spread of infectious diseases carried, for example, by mosquitoes, iv) changes of biodiversity in an urban ecosystem, etc. It is more natural to involve the damages of neighboring metropolises that have unilateral or multilateral impacts among them. One metropolis is taken up here for the sake of simplicity, without considering the “climatic externality.”

This paper has applied the economic way of thinking to an environmental problem of growing importance and has proposed a theoretical possibility to analyze heat island. My discussion has proceeded on the premise that the urban atmosphere is a composite of gaseous characteristics including heat. Sato(2006b) incorporated vegetation and technological innovations to cool urban heat islands.
2.5. Beings and Functionings of Periurban Residents Menaced by Urban Heat Island

The city itself is a complex of an infinite number of attributes. The Gorman-Lancasterian characteristics theory is the most suitable to analyze goods, such as the urban atmosphere, which are perfectly divisible and decomposable into elements as gaseous attributes. However, the characteristic availability functions is applied to any resident whose utilization differs from person to person. Consequently, each inhabitant’s functionings should be introduced as one of the important concepts à la Sen(1985) to fully appraise the value of goods or characteristics. Each resident’s physical and climatical situations differ, so I must introduce the functionings which are represented below.

Metropolitan consumers use personal computers, printers, air-conditioned rooms, drive cars and cook meals. They also watch televisions, listen to music, and make photocopies. All of these behaviors may be considered as functionings, thus, city dwellers emit heat and gases when they use their functionings. Much heat is emitted from large-sized refrigerators in households and supermarkets to store many things such as fruits, vegetables, fish, meat, poultry, dairy produces and frozen foods.

Different from Sen, an inhabitant’s beings can be represented as a vector of functionings. Let \( f_i \) be a vector of resident \( i \)'s functionings. The set of person \( i \)'s functionings is denoted as \( K_i \). Not to mention, the number of functionings \( K_i \) differs among persons. Note that \( K_i \) includes resident \( i \)'s physical ability which heavily depends upon its climate in the block where he/she lives or works, e.g., a temperature of more than 40°C in the daytime would bring critical situations for human bodies: an increase of body temperature, heat exhaustion, bad circulation, etc. One liter of water per hour could be discharged from the body when the thermometer shows above 30°C; some people could die of dehydration. Also indicated is that victims of heatstroke will exponentially increase when the mercury exceeds more than 34°C. City dwellers will want to have more water and cold drinks, to swim in a pool or in the sea, to see tropical fish in an aquarium. When the temperature approaches 40°C, the number of sunstroke victims will increase. Urban heat island will cause many residents' deaths in metropolises in the future. The number of people conveyed by ambulance was more than four hundreds in July 2006, which was the maximum in the five years, since the observation was started. Many people will be sick because they stay in rooms extremely air-cooled for a long time. Heat-sensitive persons will have to pay medical expenses when they suffer from heatstroke or other diseases.

If he/she chooses a vector of functionings, then his/her beings are generated by his/her functionings, \( f_{ik}, \forall k = 1, ..., K_i \in K_i \). As for heat emission, there are two subsets, \( K_i^E \) and \( K_i^N \) (\( K_i = K_i^E \cup K_i^N \)), i.e., the functionings belonging to \( K_i^E \) are those that emit heat, whereas, those in \( K_i^N \) do not. Different from the above examples of warming the urban air, many functionings can cool the cities. Drawing water from wells to sprinkle on the rooftops also cools the houses. Generally, 20~30% of heat enters from the windows and 10% of it flees from them. So we could make efficient use of air conditioning by employing blinds and curtains, since pulling down blinds provides excellent protection against the sun. Window glass type may well be changed to one which does not easily accept heat. These are examples for some functionings of metropolitan residents.

Remark 3. I would like to point out that the following fact is very important. Residents emit heat by utilizing some of their functionings, and at the same time, they suffer from the heat they emit. That is, some functionings \( f_{ik} \in K_i^E \) of a person could inflict pain upon his/her other functionings \( f_{ik} \in K_i^N \), by prioritizing too much the convenience
and the comfortableness as immediate profits in his or her everyday life. Humans are apt
to think only of the present and take a short view of things, and this mentality may be
one of the main causes which has brought heat island in the metropolises.

Denote $z_i^C = (z_{i1}, ..., z_{iC})$, $z_i^G = (z_{iC+1}, ..., z_{iC+G})$, and $z_i^S = (z_{iC+G+1}, ..., z_{iC+G+S})$. Denote also $\varepsilon_i = z_{iH}$. Amounts of each characteristic embodied in the goods, in the
atmosphere, an in the plants in the green area, which are consumed by resident $i$ in the
periurban metropolis is given by

$$z_i = (z_{i0}, z_i^C, z_i^G, z_i^S, z_{iH}).$$

Personal beings of inhabitant $i$ may be representable as:

$$b_i = (f_{i1}(z_i, U), ..., f_{iK_i}(z_i, U)).$$

Electricity consumption can be reduced by raising the set point of the temperature of
air conditioners in the rooms.\footnote{The power saving policies are enforced in the ward offices in Tokyo and the municipal institutions
where the temperature of the air conditioners is set at 28°C. The same is true for municipal offices.} Medical methods can be developed to help alleviate the
possible spread of tropical infectious diseases carried by vermin. These are examples of
functionings, too.

Hence, the following assumption is needed.

**Assumption 3.** For any $i \in N$ and for any $f_{ik} \in K_i$, $f_{ik}$ is strictly quasi-concave and
twice continuously differentiable on the closed convex consumption set $M_i$.

**Remark 4.** It is considered that a change in the numéraire attribute $z_{i0}$ can vary
resident $i$’s functionings. For example, consuming a huge amount of goods in high
consumption societies in developed countries can be supported from combusting enormous
quantities of fossil fuels, which can be acquired by utilizing the numéraire characteristic $z_{i0}$
and functionings. The signs of $\partial f_{ik}/\partial z_{ic}$ and $\partial^2 f_{ik}/\partial^2 z_{ic}$ depend upon what characteristic
c is, i.e., it can take a sign \{+,-,0 \} according to attribute $c$ which is good, irrelevant, or
bad, respectively, for resident $i$’s well-being to exist. If $c$ is heat, then the sign may now
be minus for many metropolitan residents in summertime because of health problems due
to an increasing temperature due to urban heat island. Assumption 3 means that the
more heat emitted into the urban air, the less functionings that residents can utilize to
enjoy their metropolitan lives. They feel quite aggravated by the sweltering heat during
the day, and they may suffer from heatstroke. Summer nights with more than 25°C often
keep them from sleep, so that they have to endure sleepless nights.

### 2.6. Resident’s Happiness Function and Valuing Personal Well-Being

Let any inhabitant $i$ have his/her Happiness Function which is assumed to depend
upon his/her being, thus, one observes

$$H_i = H_i (b_i).$$

Any person’s use of functionings can vary his/her personal happiness. In order to
obtain our desired results, I need another differentiability assumption.
Assumption 4. For any \( i \in \mathbb{N} \), \( H_i \) is strictly quasi-concave and twice continuously differentiable, with \( (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_0) \neq 0 \) for at least one \( k \in \mathbb{K} \).

Denote resident \( i \)'s hedonic shadow price or hedonic marginal willingness-to-pay (HMW) of any gaseous and nongaseous characteristic \( c \), and of any biological attribute \( s \) in greenery:

\[
\pi_{ic} = \frac{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_{ic})}{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_0)}, \quad \forall c \in \mathbb{C}
\]

\[
\pi_{is} = \frac{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_{is})}{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_0)}, \quad \forall s \in \mathbb{S}
\]

\[
\pi_{ig} = \frac{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial U) (\partial U/\partial \zeta_d) (d\zeta_d/dz_g)}{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_0)}, \quad \forall g \in \mathbb{G}
\]

\[
\pi_{ih} = \frac{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial U) (\partial U/\partial \zeta_i)}{\sum_{k \in \mathbb{K}} (\partial H_i/\partial f_{ik}) (\partial f_{ik}/\partial z_0)}.
\]

Remark 5. (i) \( \pi_{ic}, \pi_{is}, \pi_{ig}, \) or \( \pi_{ih} \) is a marginal contribution of each attribute to resident \( i \)'s marginal happiness through his/her functionings in terms of the numéraire characteristic \( z_0 \). It may correspond to a “marginal rate of substitution (MRS)” between each attribute and the numéraire characteristic \( z_0 \) in the utility theoretical context.

(ii) Note that our “MRS” is totally different from Drèze and Hagen(1978), since it involves the concepts of functionings and a happiness function à la Sen, and moreover, it can be applied to detrimental attributes too. Hence, Sato(2006a) had to replace a happiness function for a utility function. Note also that the analysis of Drèze and Hagen allows for negative MRSs of some consumers, with an additional assumption that \( \sum_i \pi_{ic} > 0 \) as expressed in our notation. This means that even if some person(s) put(s) in his/her functionings \( \pi_{ic} < 0 \) on some characteristic \( c \), the aggregate value of MRSs over residents can still be positive, i.e., they admit this attribute.

(iii) Whether inhabitant \( i \) considers a commodity or a service as good, irrelevant, or bad to his or her functionings is confirmed by the sign of \( \sum_{c \in \mathbb{C} \cup \mathbb{G}} \pi_{ic} q_{jc} \) for each good \( j \). Moreover, whether a commodity or a service is socially good or not may also be examined by summing over individuals of \( \sum_{c \in \mathbb{C} \cup \mathbb{G}} \pi_{ic} q_{jc} \) for any good or service \( j \). Now, to keep the room open to the cool air, an air conditioner is one of the necessities for our comfortable urban life under urban heat island, even if it does emit heat as a vexing by-product. Consequently, \( \pi_{ih} < 0 \) holds for many people, who feel displeased by the scorching heat due to urban warming. However, they wish to avoid this, thus, \( \sum_{c \in \mathbb{C} \cup \mathbb{G}} \pi_{ic} q_{jc} > 0 \) still prevails for \( j \) if it is an air conditioner. It cannot be helped, since everybody wants to keep his/her room cool, especially under a burning sun. It is not only heat but also the resulting humidity and high temperature that could lower lots of functionings of residents. This fact can be represented by \( (\partial f_{ik}/\partial U) (\partial U/\partial \zeta_i) < 0, \forall i \in \mathbb{N} \).

The set of feasible functionings vectors for any person is the personal capability set, i.e., opportunities to achieve personal well-being. Residents live in some block, and many of them work in other block. When they move in summertime, they may suffer from the
sweltering heat. Hence, urban warming exerts an influence on residents, wherever they are in the city.

Let $x_i$ be resident $i$’s entitlements of goods, and $X_i$ be its set. Given $x_i$ and $U$, one can represent the set of feasible beings vector, or the personal capability set of inhabitant $i$ under urban warming as:

$$B_i(x_i, U) = \{b_i | b_i = (f_{i1}(z_i, U), ..., f_{iK_i}(z_i, U)),$$

$$for some f_i in F_i and for some x_i in X_i\}.$$

Limiting my analysis to the persons’ risky aspects of living which are menaced by urban warming due to human activities, one may interpret $b_i$ as a “personal wellness index,” since $b_i$, aetris paribus, corresponds to some personal being. In our context an inhabitant enjoys his or her life by using his/her functionings, which enhance his/her happiness and well-being. The health of the population in the metropolis is not only an ultimate objective, but also a means which permits people to experience agreeable urban lifestyles. The crucial problem is that many residents’ personal capability sets would shrink due to the accelerating urban warming in the near future, i.e., $B_i^{t+1}(x_i^{t+1}, U^{t+1}) \subset B_i(t, U^t)$.

In the global warming case, Sato(2000) characterized the conditions for a socially optimal consumption of goods as well as the global ambient air in terms of characteristics including gaseous attributes. I added “climatical constraints” to confirm an optimal composition of the global atmosphere to maximize a personal happiness function, which depends upon his/her functionings. Section 3 presents the main results, i.e., a derivation of optimality conditions for the urban climate and a design of urban heat island tax/subsidy scheme.

3. HEDONIC OPTIMALITY CONDITIONS FOR METROPOLITANS UNDER URBAN HEAT ISLAND

3.1. Periurban Residents

Consider that city dwellers know the risks of man-made future urban climate changes due to urban heat island, and that they have an incentive to optimize the composition of the urban atmosphere in order to aim at achieving their personal best-being in the metropolis. Let $\delta$ be a distance from the center of the CBD. Denote $r_i(\delta)$ as the rent of one square meter of land, and each inhabitant’s rent is $r_i(\delta) L_i$, when he/she leases a lot $L_i$ from an absentee landlord. $\xi_i(\delta)$ is the transportation cost to go to whatever place the resident $i$ likes, by using his/her private car(s), and public transportation systems such as buses, subways, trains, and streetcars. For example, with his/her family, he/she visits museums or concert halls in the CBD or natural parks in the periurban zone. It is assumed that his/her commuting cost is payed by the firm in which he/she works, and that it is involved in $z_{\theta}$.$^5$

Denote $\varepsilon_i = (\varepsilon_1(\alpha_1), ..., \varepsilon_{i-1}(\alpha_{i-1}), \varepsilon_{i+1}(\alpha_{i+1}), ..., \varepsilon_{N+J+\Lambda}(\alpha_{N+J+\Lambda}))$. Denote also $\nu_i(\varepsilon_i(\alpha_i), \varepsilon_{\cdot-i}(\alpha_{\cdot-i}))$ as resident $i$’s heat abatement cost which depends upon his/her emission of heat as well as those of others. A parameter $\alpha_i > 0$ is associated with his/her effort to reduce heat emission. It is assumed that $\alpha_i$ is known only to him/her. Economizing

$^5$Usually in the urban economics, a commuting cost is not implicitly included in the income, but explicitly defined instead of the traffic cost. This model is somewhat different from that in an ordinary urban economic theory.
in power, reducing garbage, and using a bicycle or public transportations instead of a car are functionings. As heat island accelerates, city dwellers will want to buy newly developed, more efficient air conditioners, which result in reduction of heat emission. These are examples to explain \( \alpha_i \). Resident \( i \) has to pay \( t_i (\alpha_i) \) as an urban heat island tax, in order for the urban atmosphere not to be warmed so much as to be unendurable to live in.\(^6\)

Greening lands and rooftops are one of the most effective ways to cool the metropolis. Let the metropolitan government determine \( \varphi \) as the refund rate for greening the area \( A_{it} \) that resident \( i \) commissions gardener \( \ell \). Assume that the value of \( \varphi \) is decided by the scientific data about tree-planting. As defined, \( \sigma_\ell \) is gardener \( \ell \)'s greening cost per square meter, hence, \( \sigma_\ell A_{it} \) is resident \( i \)'s greening cost, and \( \varphi \sigma_\ell A_{it} \) is \( i \)'s refund for the effort to plant trees.

The set \( J \) includes all the goods and services such as electricity and water but land and transportation, and \( p_j \) is a unit price of good \( j \), then each inhabitant’s budget constraint is given by

\[
  z_{i0} = \sum_{j \in J} p_j x_{ij} + r_i(\delta)L_i + \xi_i(\delta) + \nu_i(\varepsilon_i(\alpha_i), \varepsilon_{-i}(\alpha_{-i})) + t_i(\alpha_i) + \sigma_\ell A_{it} - \varphi \sigma_\ell A_{it}.
\]

The left-hand side of the above equation signifies the value of numéraire attribute whose price is normalized to be one.

**Assumption 5.** For any \( i \in N, r_i, \xi_i, \nu_i, \varepsilon_j \) and \( t_i \) are strictly quasi-concave and continuously differentiable, with \( dr_i/d\delta < 0, d\xi_i/d\delta > 0, \partial \nu_i/\partial \varepsilon_i < 0, \partial \nu_m/\partial \varepsilon_m > 0, \forall m \in E, m \neq i, d\varepsilon_i/d\alpha_i < 0 \) and \( dt_i/d\alpha_i < 0 \).

This assumption means that \( r_i(\delta) \) has a distance decay curve, and that \( \xi_i(\delta) \) has an increasing curve of distance. The more heat is emitted, the more the urban air warms, and the more costly life becomes. This signifies that the more damages due to urban heat island, the more residents have to pay for cool air, the more tax they have to pay for alleviating the urban warming. Each resident’s effort can diminish his/her tax payment.

The maximand is the personal happiness function. Each periurban resident solves the following optimization problem:

\[
  \text{Max } H_i = H_i(b_i) \\
  \text{s.t. } U = U(E) \\
  E = \sum_{i \in N} \varepsilon_i + \sum_{j \in J} \varepsilon_j + \sum_{\ell \in A} \xi_{\ell} + \sum_{\beta \in \beta} \varepsilon_\beta \\
  z_{i0} = \sum_{j \in J} p_j x_{ij} + r_i(\delta)L_i + \xi_i(\delta) + \nu_i(\varepsilon_i(\alpha_i), \varepsilon_{-i}(\alpha_{-i})) + t_i(\alpha_i) + \sigma_\ell A_{it} - \varphi \sigma_\ell A_{it} \\
  x_{ij} \geq 0, \forall j \in J \\
  A_{it} \geq 0, \forall \ell \in A.
\]

\(^6\)See Sandmo(2000) for some related issues of taxes and alternatives to improve the environment.
Now our first result is presented.

**Proposition 1.** For any periurban resident \( i \in \mathbb{N} \), an individually optimal consumption of goods composed by Gorman-Lancasterian gaseous and nongaseous attributes, and of the green area as a complex of biological attributes is characterized as: \( \forall j \in J, \forall \ell \in \Lambda \)

\[
\begin{align*}
\sum_{c \in C_{jG}} \pi_{ic} q_{jc} & \leq p_j, \quad \left( \sum_{c \in C_{jG}} \pi_{ic} q_{jc} - p_j \right) x_{ij} = 0 \\
\sum_{c \in S_{jG}} \pi_{ic} q_{ic} & \leq \sigma_{\ell}(1 - \varphi), \\
0 & = \left\{ \sum_{c \in S_{jG}} \pi_{ic} q_{ic} - \sigma_{\ell}(1 - \varphi) \right\} A_{i\ell} \\
\frac{dt_i}{d\alpha_i} & \leq -\frac{\partial v_i}{\partial \varepsilon_i} \frac{d\varepsilon_i}{d\alpha_i} + \left( \frac{dt_i}{d\alpha_i} + \frac{\partial v_i}{\partial \varepsilon_i} \frac{d\varepsilon_i}{d\alpha_i} \right) \alpha_i = 0 \\
L_i & \leq -\frac{d\xi_i}{d\delta} + \left( \frac{d\xi_i}{d\delta} \right) \delta = 0 \\
r_i & \leq -\rho_i \sigma_{\ell}(1 - \varphi), \quad \{ r_i + \rho_i \sigma_{\ell}(1 - \varphi) \} L_i = 0.
\end{align*}
\]

**Remark 6.** (i) The conditions presented are not only necessary but also sufficient from the assumptions on the functions. In the first equations, \( \pi_{ic} \) signifies a hedonic shadow price of an attribute acquired by utilizing inhabitant \( i \)'s numéraire characteristic through his/her functionings. The left-hand side of the first equation is the sum of resident \( i \)'s marginal evaluations of the nongaseous attributes embodied in one unit of a good, as well as of the gaseous attributes released when the good is produced. Notice that the first formulae verify that any resident considers heat and gases as gaseous characteristics emitted when consuming one unit of good \( j \). The first conditions mean that the unit price of the good is equal to the sum of marginal contributions of attributes to his/her happiness through his/her functionings. The conditions assure a Pareto optimality for a quantity of each good, and give a basis upon which goods household \( i \) chooses to buy. (ii) The second conditions signify that individual \( i \)'s marginal evaluation of species as biological attributes by having the area \( A_{i\ell} \) of his/her land \( L_i \), planted by a gardener \( \ell \) is equal to his/her greening cost per square meter minus the refunded cost. The term, \( \varphi \sigma_{\ell} \) may be called a “urban heat island (alleviating) subsidy,” since it represents the reward according to the person’s effort to plant trees in a part of his/her land. Many residents suffer from the fierce heat in summertime, if he/she feels very displeased by the boiling weather due to urban heat island. (iii) The conditions about \( t_i \) show that city dweller \( i \)'s marginal evaluation of emitting a unit of heat is a match for his/her marginal urban heat island tax. The next conditions let us know the lot size that the resident decides to lease from an absentee landlord. These are the equilibrium conditions of residential location. It is easily seen that \( L_i \) is determined by the distance, the rent and the traffic cost that inhabitant \( i \) has to pay. The last two formulae determine the equilibrium rent in the metropolis. Note that the more rent increases, the more the area is greened, and the less heat is emitted. As is explained in detail in Section 3, greening a rooftop or a garden as a part \( \rho_i \) of his/her lot size, any resident can cool his/her house, which results in saving power. Thus, an incentive is given to an inhabitant to have a part of his/her land planted with trees and flowers from motives of selfishness.
3.2. Offices, Manufacturers and Farmhouses as Producers

A framework that I earlier employed in Sato(2006a) is used to involve the phenomenon of urban warming due to heat released by the producers. We present the optimization by profit maximizing producers to supply one good with an optimal product quality to consumers. Let producer \( j \) (gardener \( \ell \)) produce good \( j \) (service \( \ell \)) by using \( L_j \) and \( x_{j0} = (L_{\ell} \text{ and } x_{\ell0}) \) as inputs, and the price of \( x_{j0} = (x_{\ell0}) \) is normalized to be one, with \( \sum_{j \in J} x_{j0} + \sum_{i \in A} x_{i0} \leq \sum_{j \in J} \tilde{x}_{j0} \). Then, \( x_{j0} = (x_{\ell0}) \) is a \textit{numéraire attribute} that producer \( j \) (gardener \( \ell \)) uses as an input.

Let \( y_j = (x_{j0}, L_j, x_j, q_{j1}, \ldots, q_{jC}, q_{jC+1}, \ldots, q_{jC+G}, q_{jh}) \) be producer \( j \)'s input-outout vector, then it produces a good \( j \) as an output to maximize its profit subject to the production function:

\[
\psi_j = \psi_j (x_{j0}, L_j, x_j, q_{j1}, \ldots, q_{jC}, q_{jC+1}, \ldots, q_{jC+G}, q_{jh}) \leq 0 \tag{16}
\]

where \( q_{jc}, \forall c \in G, \) is an amount of a gas emitted in the urban atmosphere when it produces one unit of good \( j \), and \((q_{jC+1}, \ldots, q_{jC+G}, q_{jh})\) is a vector of intangible attributes. Meanwhile, \((q_{j1}, \ldots, q_{jC})\) is a vector of tangible nongaseous characteristics embodied in one unit of good \( j \). Any producer therefore jointly produces a good and emit heat and gases as intangible attributes. The production function may not be convex, but the difficulties arising from nonconvexities are not treated here, so I must make an assumption.

\textbf{Assumption 6.} For any \( j \in N, \psi_j \) is convex and twice continuously differentiable on the closed convex production set \( Y_j \), with \( \partial x_{j0}/\partial q_{jc} > 0, \forall c \in C \cup G, c \neq j' \). Furthermore, \( x_j > 0 \) implies \( x_{j0} > 0 \) and \( L_j > 0 \), and \( \forall \Delta \in R_+, (y_j | \psi_j (y_j) \leq 0, x_{j0} \leq \Delta, L_j \leq \Delta) \) is compact.

We assume that \( \pi_{ic} \) and \( \pi_{ig} \) are truthful, since all goods are private goods or publicly provided goods such as gas, water and electricity, for which the residents have to pay public utility charges. Hence, they cannot have for free. When \( x_{ij} > 0 \), \( p_j \) could be computed as \( \sum_{c \in C \cup G} \pi_{ic} q_{jc} \) from \textbf{Proposition 1}, then the profit maximization problem for the producers are given by\(^7\)

\[
\text{Max } P_j = \sum_{i \in N} \sum_{c \in C \cup G} \pi_{ic} q_{jc} x_{ij} - x_{j0} - r_j(\delta) L_j
\]

\[
- \nu_j (\varepsilon_j (\alpha_j), \varepsilon_{-j} (\alpha_{-j})) - t_j (\alpha_j) - \mu_j \delta x_j
\]

\[
- \chi \sigma_j A_j + \chi \varphi \sigma_j A_j + (1 - \chi) \omega L_j F
\]

\[
\chi = 0 \text{ if } j \in J_F \text{ and } \chi = 1 \text{ if or } j \notin J_F.
\]

\textbf{Remark 7.} (i) The first term of the R.H.S. is revenue. \( x_{j0} \) is the amount of labor used as an input, and \( r_j(\delta) L_j \) is the rent of land, where \( L_j \) is variable as an input. Denote \( \varepsilon_{-j} = (\varepsilon_1 (\alpha_1), \ldots, \varepsilon_{j-1} (\alpha_{j-1}), \varepsilon_{j+1} (\alpha_{j+1}), \ldots, \varepsilon_{N+J_\Delta} (\alpha_{N+J_\Delta}) \). Let \( \nu_j (\varepsilon_j (\alpha_j), \varepsilon_{-j} (\alpha_{-j})) \) be \( j \)'s heat abatement cost, where \( \alpha_j > 0 \) is a parameter only known to \( j \) to reduce heat

\(^7\)To construct the producer's profit function, I followed Drèze and Hagen(1978, p.510) who wrote that "the implicit price could be computed... and they would in equilibrium be the same for all consumers. So we do not have to make price differentiation among consumers." This fact follows from their assumption of nonsingularity of the technological matrix. If the matrix \( q_1 \) and \( q_2 \) are nonsingular, then they have an inverse matrix. In our model \( q_1 \) and \( q_2 \) are not nonsingular, so we assume the truthful revelation of \( \pi_{ic}, \forall c \in C \cup G, \) and \( \pi_{ia}, \forall s \in S, \forall i \in N.\)
emission. Note that \( \nu_j \) depends on the heat emissions of the rest of the city. It may be interpreted as an external cost to buy, for example, more efficient power saving air conditioners. Urban heat island tax \( t_j \) is a function of \( \alpha_j \) which represents firm \( j \)'s effort to decrease an emission of heat when producing and transporting \( x_j = \sum_{i \in \mathbb{N}} x_{ij} \) units of good \( j \). More examples to explain \( \alpha_j \) are in order: producer \( j \) encourages his/her staff to commute by bicycle, to use hybrid or fuel cell cars as delivery vans, and to choose energy-saving type of personal computers in the office.

(ii) Let \( \mu_j > 0 \) be a unit cost of transportation. In the above equation it is necessary to include \( \mu_j \delta x_j \) as transportation cost in the above equation, since delivery of goods result in emitting heat, GHGs such as CO\(_2\), and CH\(_4\).\(^8\) It is generally accepted that midtown hotels, hospitals and office buildings use more computers and air conditioners than residents and gardeners in the periurban belt. The former would emit more heat and gases into the urban atmosphere so as to cool their hotels, hospitals and offices, as urban heat island accelerates in the near future. As producers, offices offer services, manufacturers supply products, and farmhouses make agricultural products.

(iii) \( \sigma_j A_j \) is firm \( j \)'s greening cost, and \( \varphi \sigma_j A_j \) is the refund to firm \( j \). Denote \( L_{jF} \equiv \Pi_j L_j \) as \( j \)'s farmland, where \( \Pi_j \) is a proportion of \( L_j \). Let \( \omega L_{jF} \) \((0 < \omega < 1)\) be a reward given by the metropolitan government to farmhouse \( j \) which has not turned its farmland into housing. Let also \( J_F \) be the set of farmhouses that are exempted from the obligation to green a part of their own lands.

Here I need another assumption.

Assumption 7. For any \( j \in \mathbf{J}, r_j, \nu_j, \varepsilon_j, \) and \( t_j \) are strictly quasi-concave and twice continuously differentiable with \( dr_j/d\delta < 0, \partial \nu_j/\partial \varepsilon_j < 0, \partial \nu_m/\partial \varepsilon_m > 0, \forall m \in \mathbf{E}, m \neq j, d\varepsilon_j/d\alpha_j < 0 \) and \( dt_j/d\alpha_j < 0 \).

In the presence of tangible and tangible attributes, I have the following result.

Proposition 2. For any periurban producer \( j \in \mathbf{J}, \) necessary conditions for Pareto optimal product quality in terms of tangible and intangible attributes are: \( \forall c \in \mathbf{C}, c \neq \)

\(^8\)CO\(_2\) emitted from the transportation branch is 20% in Japan.
\[ j', \forall g \in G, g \neq j', h \neq j' \]

\[
\sum_{i \in N} \pi_{ic} x_{ij} \leq \frac{\partial x_{j0}}{\partial q_{jc}} + r_j \frac{\partial L_j}{\partial q_{jc}} + \mu_j \delta \frac{\partial x_j}{\partial q_{jc}}
\]

\[
0 = \left( \sum_{i \in N} \pi_{ic} x_{ij} - \frac{\partial x_{j0}}{\partial q_{jc}} - r_j \frac{\partial L_j}{\partial q_{jc}} - \mu_j \delta \frac{\partial x_j}{\partial q_{jc}} \right) q_{jc}
\]

\[
\sum_{i \in N} \pi_{jg} x_{ij} \leq \frac{\partial x_{j0}}{\partial q_{jg}} + r_j \frac{\partial L_j}{\partial q_{jg}} + \mu_j \delta \frac{\partial x_j}{\partial q_{jg}}
\]

\[
0 = \left( \sum_{i \in N} \pi_{jg} x_{ij} - \frac{\partial x_{j0}}{\partial q_{jg}} - r_j \frac{\partial L_j}{\partial q_{jg}} - \mu_j \delta \frac{\partial x_j}{\partial q_{jg}} \right) q_{jg}
\]

\[
\sum_{i \in N} \pi_{ih} x_{ij} \leq \frac{\partial x_{j0}}{\partial q_{jh}} + r_j \frac{\partial L_j}{\partial q_{jh}} + \nu_j \frac{\partial x_j}{\partial q_{jh}} + \mu_j \delta \frac{\partial x_j}{\partial q_{jh}}
\]

\[
0 = \left( \sum_{i \in N} \pi_{ih} x_{ij} - \frac{\partial x_{j0}}{\partial q_{jh}} - r_j \frac{\partial L_j}{\partial q_{jh}} - \nu_j \frac{\partial x_j}{\partial q_{jh}} - \mu_j \delta \frac{\partial x_j}{\partial q_{jh}} \right) q_{jh}
\]

\[
\frac{dt_j}{dz_j} \leq - \frac{\partial \nu_j}{\partial z_j} \frac{dz_j}{dz_j} \Delta \nu_j \alpha_j = 0
\]

\[
L_j \leq \frac{\mu_j x_j}{\partial r_j / \partial \delta}, \quad \left( L_j + \frac{\mu_j x_j}{\partial r_j / \partial \delta} \right) \delta = 0
\]

\[
r_j \leq - \chi \rho_j \sigma_j (1 - \varphi) - \mu_j \delta \frac{\partial x_j}{\partial L_j} - (1 - \chi) \omega \Pi_j
\]

\[
0 = \begin{cases} 
    r_j + \chi \rho_j \sigma_j (1 - \varphi) + \mu_j \delta \frac{\partial x_j}{\partial L_j} \\
    + (1 - \chi) \omega \Pi_j \delta \end{cases}
\]

\[
\chi = 0 \text{ if } j \in J_F \text{ and } \chi = 1 \text{ if } j \notin J_F.
\]

Remark 8. (i) The first equations establish a Pareto optimality for an amount of each attribute and determine a vector of optimal nongaseous characteristics embodied in the goods supplied by producer \( j \). The L.H.S. of the first equation is the marginal revenue which is the aggregate of the residents’ marginal evaluations of an infinitesimal change in an attribute embedded in \( x_j \). Its R.H.S. is the marginal cost in terms of the numéraire characteristic and the land to produce \( q_{jc} \), as well as \( j \)'s marginal transportation cost. \( \sum_{i} \pi_{ic} x_{ij} \) is the marginal social value of good \( j \), which is the sum of the personal evaluations of a change in an attribute when the quantity of good \( x_j \) is produced.

(ii) The next four equations show a pareto optimal quantity of heat as intangible attribute and gases as gaseous attributes. The L.H.S. is the social value of the \( g \)th gas or heat, and the R.H.S. consists of four terms: the first two terms are the marginal cost in terms of \( x_{j0} \) and \( L_j \), the third term means the marginal damage to emit heat or gas \( g \), and the last term is the marginal transportation cost when producing \( x_j \) units of good \( j \). As in Proposition 1, \( t_j \) is the urban heat island tax of firm \( j \), and the formulae of \( L_j \) determine the equilibrium lot size. The last three equations determine the equilibrium land rent, which is equal to the sum of the terms of greening cost \( \sigma_j / m^2 \) and marginal
transportation cost (MTC) of producer \( j \notin J_F \). Whereas it equals to the terms of MTC and the reward given to farmhouse \( j \in J_F \). The amount of \( \omega \Pi_j \) is given as a subsidy to farmhouse \( j \) for preserving its farmland in the periurban area, which could be expected to somewhat mitigate urban heat island.

3.3. Periurban Landscape Gardeners

Next, efficiency conditions for periurban landscape gardeners are derived. Their job is to plant trees in areas of lands that residents or producers possess, so they are exempted from the obligation of greening a part of their own lands in my model. They supply plants as biological, and therefore nongaseous attributes. Let \( r_{\ell, c} \) be the land rent, where \( r_{\ell, c} \) is the rent per square meter and \( L_c \) is the land leased from the absentee landlord. Denote \( \xi_{\ell, c} = (\xi_{1, \alpha_1}, \ldots, \xi_{\ell, -1}(\alpha_{j-1}), \xi_{j, +1}(\alpha_{j+1}), \ldots, \xi_{N+J+\Lambda}(\alpha_{N+J+\Lambda})) \). Let \( \nu_{\ell}(\xi_{\ell, \alpha_\ell}, \xi_{-\ell}(\alpha_{-\ell})) \) be gardener \( \ell \)'s abatement cost, where \( \alpha_\ell > 0 \) is a parameter only known to gardener \( \ell \). Landscape gardeners can attempt to serve green areas to residents by using a new technology which does not emit too much heat. Let \( A_{\ell} \) be their transportation cost, where \( \mu_{\ell} \) is a unit cost of transportation and \( A_{\ell} = \sum_{i \in J} A_{i, \ell} \). Thus, they emit trace gases such as CO\(_2\) into the air, when they serve and transport their garden plants. Any gardener serves a green area to residents to maximize his/her profit subject to the production function

\[
\psi_{\ell} = \psi_{\ell}(x_{i, 0}, L_{\ell}, A_{\ell}, q_{i, C+1}, \ldots, q_{i, C+G}, q_{i, C+G+1}, \ldots, q_{i, C+G+S}, q_{i, h}).
\]

Hence, each gardener solves the optimization problem:

\[
\text{Max } P_{\ell} = \sum_{i \in J} \sum_{c \in S \setminus G} \pi_{i, c} q_{i, c, \ell} A_{i, \ell} - \{x_{i, 0} + r_{\ell}(\delta)L_{\ell} + \nu_{\ell}(\xi_{\ell, \alpha_\ell}, \xi_{-\ell}(\alpha_{-\ell})) + t_{\ell}(\alpha_\ell) + \mu_{\ell} \delta A_{\ell}\}.
\]

Two assumptions are needed for this maximization problem.

**Assumption 8.** For any \( \ell \in \Lambda \), \( \psi_{\ell} \) is convex and twice continuously differentiable on the closed convex production set \( Y_{\ell} \), with \( \partial \psi_{\ell}/\partial q_{i, c} > 0, \forall c \in S \setminus G, \ c \neq \ell \). Furthermore, \( A_{\ell} > 0 \) implies \( x_{i, 0} > 0 \) and \( L_{\ell} > 0 \), and \( \forall \Delta \in \mathbb{R}_+, \{y_{\ell}|\psi_{\ell}(y_{\ell}) \leq 0, x_{i, 0} \leq \Delta, L_{\ell} \leq \Delta\} \) is compact.

**Assumption 9.** For any \( \ell \in \Lambda \), \( r_{\ell}, \nu_{\ell}, \xi_{\ell} \) and \( t_{\ell} \) are strictly quasi-concave and twice continuously differentiable with \( dr_{\ell}/d\delta < 0, \partial \nu_{\ell}/\partial \xi_{\ell} < 0, \partial \nu_{m}/\partial \xi_{m} > 0, \forall m \in E, m \neq \ell, \partial t_{\ell}/\partial \alpha_{\ell} < 0 \) and \( \partial t_{\ell}/\partial \alpha_{\ell} < 0 \).

Then I obtain the following result.

**Proposition 3.** For any periurban landscape gardener \( \ell \in \Lambda \), necessary conditions for Pareto optimal quality of planted green area as a complex of biological attributes
Remark 9. As in Proposition 2, some of the equations are reminiscent of Samuelson’s Conditions, since attributes, including biological ones are public goods. Gardeners make their products and transport them, so they have to pay for transportation, $\mu_\ell \delta A_\ell$, where $\mu_\ell$ is a unit cost of transportation. They plant trees on the lands of private houses. The equations establish a Pareto optimality for an amount of each attribute and determine a vector of optimal quality characteristics that any gardener can supply its biological product to residents. The R.H.S. of the first equation is the marginal cost composed of three terms: the first is the marginal cost of the numéraire attribute and the second is the marginal cost of land to supply one unit of plant as a biological attribute, and the third is the marginal transportation cost. The first two equations signify the marginal social value in terms of the numéraire attribute, where the marginal social value is the sum of the personal evaluations of a change in each biological characteristic. The next eight equations have the same implications as for the producers. As in the above propostions, the last two formulae define the equilibrium rent, which is equal to gardener $\ell$’s MTC.

3.4. The Metropolitan Government with an Urban Heat Island Tax/Subsidy Scheme

Here explained is the urban heat island tax/subsidy scheme. For that purpose, define the monetary damages due to heat island as the sum of costs to deal with public damages: $\Phi \equiv \sum_{\beta \in \beta} D_\beta(U(E))$ and the sum of abatement costs to cope with private damages:
\[ \Psi = \sum_{e \in \mathbf{E}} \nu_e(\varepsilon_e(\alpha_e), \varepsilon_{-e}(\alpha_{-e})), \] where \( e \) is a generic index for any heat emitter in the metropolis. Examples of public damages and private damages are the inundation of a subway station, houses flooded above floor level or up to the floorboards. \( \Phi \) embraces economic losses in the deaths of people and domesticated animals due to heat waves.\(^9\) Also, \( \Psi \) includes the costs of cooling installations in stockyards and of increasing water consumption due to cooling them. The social damage due to urban heat island therefore is \( \Phi + \Psi \). Hence, the problem of social cost to be minimized is

\[ \text{Min } \{ \Phi + \Psi + \Gamma + \Omega \} \]

where \( \Gamma(A_P) \) is the cost to plant the area \( A_P \) with trees, and \( \Omega(W_P) \) is the cost to revive the amount of water, \( W_P \), in our periurban metropolis.

**Assumption 10.** \( D_\beta, \Gamma, \text{ and } \Omega \) are strictly quasi-concave and twice continuously differentiable with \( dD_\beta/dU > 0, \forall \beta \in \beta, \partial \varepsilon_\beta/\partial A_P < 0, \partial \varepsilon_\beta/\partial W_P < 0, d\Gamma/dA_P > 0 \text{ and } d\Omega/dW_P > 0. \)

Since I seek for socially optimal quantities of greenery, water, and heat emission, the first order conditions are:

\[ \sum_{\beta \in \beta} \frac{dD_\beta(U)}{dU} \frac{\partial U}{\partial (E)} \frac{\partial \varepsilon_\beta}{\partial A_P} + \frac{d\Gamma(A_P)}{dA_P} = 0 \] (17)

\[ \sum_{\beta \in \beta} \frac{dD_\beta(U)}{dU} \frac{\partial U}{\partial (E)} \frac{\partial \varepsilon_\beta}{\partial W_P} + \frac{d\Omega(W_P)}{dW_P} = 0 \] (18)

and

\[ \sum_{\beta \in \beta} \frac{dD_\beta(U)}{dU} \frac{\partial U}{\partial \varepsilon_e} + \sum_{e \in \mathbf{E}} \frac{\partial \nu_e(\varepsilon_e(\alpha_e), \varepsilon_{-e}(\alpha_{-e}))}{\partial \varepsilon_e} = 0. \] (19)

The first term of the formula (17) signifies the marginal damage of losing one square meter of green area, and the second term is the marginal cost of greening an area with an additional one square meter of the area. Similarly, the first term of Eq.(18) is the marginal damage of losing one ton of water, and the second term means the marginal cost to revive one ton of water in the metropolis.

Here I present the main result.

**Theorem.** Urban heat island tax is of the form à la Groves represented by

\[ t_e(\alpha_e) = \int_0^{\alpha_e} \frac{\partial \nu_e(\varepsilon_e(a_e), \varepsilon_{-e}(a_{-e}))}{\partial \varepsilon_e} da_e + Q_e(a_{-e}), \forall e \in \mathbf{E} \]

where \( Q_e(a_{-e}) \) is a constant of integration independent of \( a_e \).

\(^9\)In 2003 Europe was overcome by abnormal weather with record fierce heat and fatalities numbered at more than 13,000 in France. Paris especially experienced violent heat wave with more than 40°C. A heavy death toll was recorded because many people could usually air-conditioning in not so hot summers in Paris. In July 2007 Europe experienced again heat wave with more than 40°C which resulted in many fatalities of the elderly heat-sensitive people in Rumania.
Proof: By adopting the Laffont’s (1982) differential method, one observes from Propositions 1–3 that
\[
\sum_{e \in E} \left\{ \frac{\partial v_e(\varepsilon_e(\alpha_e), \varepsilon_e(\alpha_e))}{\partial \varepsilon_e} \frac{d\varepsilon_e}{d\alpha_e} + \frac{dt_e(\alpha_e)}{d\alpha_e} \right\} = 0. \tag{20}
\]
Integrating this yields
\[
\sum_{e \in E} t_e(\alpha_e) = -\sum_{e \in E} \left\{ \int_0^{\alpha_e} \frac{\partial v_e(\varepsilon_e(\alpha_e), \varepsilon_e(\alpha_e))}{\partial \varepsilon_e} \frac{d\varepsilon_e}{d\alpha_e} da_e + Q_e(\alpha_e) \right\}.
\]
Suppose that there exists a unique solution to the above problem of social cost. As we aim to find the urban heat island tax corresponding to the social optimum, integrating and substituting Eq.(21) in the above equation gives
\[
\sum_{e \in E} t_e(\alpha_e) = \sum_{\beta \in \beta} \int_0^{\alpha_e} \frac{dD_{\beta}(U)}{dU} \frac{d\varepsilon_e}{d\alpha_e} da_e + Q \tag{21}
\]
where \(Q\) is a constant of integration.

Consequently, the sum of urban heat island taxes is represented by
\[
\sum_{e \in E} t_e(\alpha_e) = \sum_{\beta \in \beta} D_{\beta}(U(E)) + R \tag{22}
\]
where \(R\) is a constant of integration. Q.E.D.

Claim. \(R\) can be interpreted as the total subsidies which can be given to the collaborators of tree planting and of preserving farmlands in the city.

\[
S = \sum_{i \in N} \sum_{e \in A_i} \varphi_i A_i + \sum_{j \in J} \varphi_j A_j + \sum_{j \in F} \omega_j L_j. \tag{23}
\]
Hence, subsidies are given to residents, offices and manufacturers as cooperation for their efforts to have trees and flowers planted in the required percentage of their land lots. The third term is the sum of rewards given to farmhouses to preserve their farmlands. \(S\) is the sum of heat island subsidies to cool down the metropolis. An amount of \(R - S\) is used to undertake public works at the cost of \(\Gamma(A_P)\) and \(\Omega(W_P)\).

Remark 10. What is important is that the R.H.S. of the formula (22) does not depend upon any unobservable parameter \(\alpha_e\), thus, it is immune to whatever manipulation on the part of the residents, producers and gardeners. The problem of preference revelation problem under incomplete information need not be discussed here. As for monitoring, \(\varepsilon_e\) can be partially measured by the amounts of gas and electricity used by each agent. Then, the tax/subsidy scheme is said to be strategy proof. Another important feature is that the tax levied can fully cover social damage, and the part of the tax overpaid \(R\) can be redistributed to the contributers in order to cool the metropolis as shown above.

Allow me to enumerate some issues for further research. First of all, this paper hopes to be a qualitative rather than quantitative one and my model is operational. Nobody cannot recognize how much the heat one emits contributes to urban warming. Further,
urban economic theoretical analysis must be made to realistically involve urban heat island and land use with a knowledge of this phenomenon. A model incorporating both greening and water management in more detail was given by Sato(2006b). Finally, whether an optimal urban atmospheric quality can be implemented in a dynamic context will be one of the main concerns of a consequent paper which will show that the composition of characteristics in the urban atmosphere can be intertemporally optimized by adjusting each component. Thus, one has to design a dynamic process to implement the urban hedonic optimality conditions.\(^{10}\)

Now is the time when our civilization and urbanization have been changing the urban climate, which cannot but entail modifications of our lifestyles. The situation that we stand in is very different from that of Pre-Industrial Revolution.\(^{11}\) I have shown efficiency conditions, but have not characterized the climatical optimality. I do not at all insist that the human beings can artificially control the urban atmospheric compound of gaseous characteristics. What I have done is just to derive theoretically the hedonic optimality conditions in an economic sense.

**Acknowledgement**

The previous version of this paper was presented at the Regional Science Workshop in Sendai held at the Graduate School of Information and Sciences, Tohoku University, September 10, 2003. The author would like to thank Komei Sasaki, Kei Fukuyama and the participants at the workshop for valuable comments and suggestions, which substantially improved the earlier version of the paper. The author gratefully acknowledges to Christopher Green for his insightful comments on an earlier draft. The revised version was delivered at the annual meeting of the Society for Environmental Economics and Policy Studies held at University of Tokyo, September 27, 2003. The further revised paper was presented at the annual meeting of the Japanese Economic Association held at Meiji University, October 13, 2003. Some revisions were made thereafter. Special thanks are due to two anonymous referees for many specific comments on earlier versions of this paper.

**Postscript**

The author laments the too early death of Jean-Jacques Laffont who was a public economist as well as a mathematical economist of worldwide fame. Henceforth, he should have much to do in numerous branches of economics, especially in environmental economics. It is very regrettable that he died in the prime of his life. May his soul rest in Heaven. This paper is dedicated to Jean-Jacques Laffont.

\(^{10}\)Sato(2005) proposed the hedonic MDP Procedures for adjusting quality attributes and analyzed their incentive properties. Furthermore, Sato(2000), (2001) and (2007a) presented tâtonnement and nontâtonnement processes for the adjustment of GHGs as gaseous attributes which compose the global atmosphere. See also Fujigaki and Sato(1981), (1982) and Sato(1983) for dynamic procedures for public goods.

\(^{11}\)Rifkin’s(2003) idea of The Hydrogen Economy is superb, when it comes to the issue of how to renovate thoroughgoing ways of living and lifestyles concerning our utilization of energies. However, The Solar Economy is more desirable to come, which is sustainable in the strict sense of the word. See Scheer(1993), (2001) and (2002).
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the autumn meeting of the Japanese Economic Association to be held at Nihon University, September 24, 2007.


