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Optimal biomass plantation replanting policy using dynamic programming

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ABSTRACT

Optimal utilization of existing cropland can reduce climatic impacts, including those arising from land-use change due to encroachment into pristine ecosystems. This work presents *dynamic programming* (DP) method to obtain an optimum replanting policy that has minimum CO_2 emission over a finite time horizon for commercial agriculture plantations. The periodic replanting of fuel crops is an area of interest, as CO_2 emissions and commercial considerations are two important factors that should be balanced in considering the development of a policy. With the development of a DP model, the preceding problem of finding the optimum replanting policy can be solved. A Malaysian oil palm plantation is used as illustrative case study.

1. Introduction

The adverse environmental impacts of global warming that are associated with greenhouse gas (GHG) emission have promoted extensive efforts to reduce CO_2 emissions. Increasing energy use coupled with CO_2 emissions from fossil fuel make switching to low-carbon fuels a high priority (Raupach et al., 2007). However, converting pristine ecosystems into bio-fuel plantation releases CO_2 as a result of burning or microbial decomposition of organic carbon stored in soil and plant biomass, as well as the use of fossil fuels during plantation (Reijnders and Huijbregts, 2008). It is estimated that the time required to repay this “carbon debt” through displacement of fossil fuels by biofuels varies from 17 years (sugarcane ethanol) to as long as 423 years (palm biodiesel), depending on the type of ecosystems (e.g. tropical rainforest in Indonesia and Malaysia for palm biodiesel) that are being converted (Fargione et al., 2008). Hence, it is important that for policy makers to address emissions from land-use change due to increased demand for biofuels. It is also important to optimize the use of current agricultural land, so as to minimize further encroachment into pristine ecosystems for purposes of capacity expansion.

Some recent work has reported GHG emissions reduction through the land-use change due to biofuel plantation. For example, Kauffman et al. (2014) showed how emission from indirect land-use change can potentially be reduced by producing food and bioenergy from biochar amended soils. Humpenöder et al. (2013) studied the impact of GHG emissions from land-use change on the overall GHG performance of 1st generation biofuels for the European Union (EU). However, the aforementioned work is only focus the relationship between GHG emission and land-use change. Therefore, a systematic method to optimize the use of existing cropland is needed, since the requirement for biofuel is expected to grow along with general energy demand. One such tool that could be used is *dynamic programming* (DP), which was developed by Bellman (1957) in the early 1950s as a mathematical technique for the optimization of multi-stage processes. The technique can determine the optimum solution for *n-variable* problem by breaking it into *n stages*, with each stage comprising a simple

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sub-problem which can be solved using the same general principle. In effect, DP provides a decomposition strategy for large optimization problems. Since then, it has been used in many areas of work. For example, DP was used in process control since it is less time consuming and exhibits exact optimization character as compared with other optimization algorithms (Favre and Peuportier, 2014). Rivotti and Pistikopoulos (2015) presented an algorithm for explicit model predictive control of hybrid system based on recent development in constraint DP and multi-parametric programming. DP optimization was also used for the control of heating system in low energy building, in order to achieve the minimum electrical cost, or carbon emission of heating during the winter period (Favre and Peuportier, 2014). A bi-objective DP model was formulated to find the optimal aircraft acquisition decision (lease or purchase) by minimizing green fleet index and maximizing profit, which could assist airlines in decision making for being more environmental friendly (Khoo and Teoh, 2014). Serafini (2006) made use of DP to address problem of hazardous materials travelling, in order to identify an optimal paths that will minimize both the path length (which leads to lower cost and time) and risk of damages due to accidents. DP was also used to prove the optimality condition for a resource conservation problem (El-Halwagi et al., 2003). In a recent work, DP was used to develop a dynamically efficient energy management system to achieve optimal power allocation between energy sources, while adhering to component requirements and maintaining the required operational performance (Fares et al., 2015).

Models have been proposed to aid in the planning of crop replanting cycles considering the GHG emissions. For example, Pordesimo and Noble (1990) developed a simplified robust simulation model for planning coconut planting and replanting strategies under conditions of data sparsity. Simulation results were noted to disagree with traditional practices. Williams et al. (1999) developed a systematic approach to plan sorghum replanting considering risk aspects. Popp et al. (2006) determined profit-optimal replanting strategies for soybean. However, such models often address traditional agricultural issues of profit and risk, and have rarely been used to account for carbon uptake. Ludin et al. (2014) examined the potential renewable energy resources for the palm oil cultivation process. The results showed that exploiting renewable energy technologies in plantation operations reduce up to 750 t CO_2-eq per year. Petsri et al. (2013) estimated the carbon stock and greenhouse gas emission profile throughout the complete cropping cycle of rubber plantations. Permpool et al. (2016) assessed the implication of oil palm plantation area requirement, regions most suitable for its expansion and related GHG emission in Thailand.

In this work, DP is used to model planting policy agricultural crop, with the aim to reduce CO_2 emissions. The model is intended for use by various decision makers – e.g., plantation owners to determine their own replanting policies, or government agencies to determine best practices that can be used as general recommendations for plantation management. Note that CO_2 is absorbed and released in various agricultural activities. First, through the process of photosynthesis, plants convert CO_2 into organic compounds using the energy from sunlight. Next, the use of chemicals such as fertilizers and herbicides during cultivation, as well as transportation fuel during harvesting, will release CO_2 to the atmosphere. CO_2 is also released during the replanting process (where crops are cut down) as well as during the clearing of pristine ecosystems (e.g., rainforest or swamp) for new plantations. Note also that during the replanting process, the rate of carbon capture and release varies with the age of the trees. Since DP considers all possibilities in reaching the optimum value, the solution obtained could include replanting the trees at its early age, although it would be clearly uneconomical to do so. This is mainly due to the net carbon release that is much smaller at the early stage, and thus it would be far better to replant the trees more frequently in the long run. For an economically viable solution, a modification is needed for DP in order to exclude those unfavourable alternatives.

In recent years, some planning works that consider CO_2 emission have been reported. These include the use of *pinch analysis* techniques for carbon-constrained energy sector planning (Tan and Foo, 2007), retrofit planning of carbon capture system (Tan et al., 2009), as well as the storage planning of capture CO_2 emission (Ooi et al., 2013; Shenoy and Shenoy, 2012). Another similar work was the carbon footprint reduction for manufacturing processes (Ludwig et al., 2009). Note however that in the agricultural sector, not many works have been reported for CO_2 emission reduction. Henson (2009) first reported the greenhouse gas emissions associated with the oil palm plantation in Malaysia. Wong et al. (2011) later proposed a graphical technique for carbon-constrained agricultural planning. However, these works do not report the optimum replanting policy that should be taken by the plantation company in order to achieve the minimum CO_2 emission, which is the main subject of this work.

In this paper, DP is adopted to determine replanting policy for crops, in order to minimize CO_2 emissions. New constraints are proposed for the DP model, so to allow only trees of certain age range will be considered for replanting, and thus arrives with an economically viable solution. To incorporate actual industrial practices, incentives from government (in the form of carbon credits) are also considered in identifying an optimum plantation policy. A case study on Malaysia oil palm plantation is used as illustration; however, the model itself is generic, and can be used for determining optimal replanting schedules for other crops.

2. General problem statement

The problem definition in finding the optimum planting policy is stated as follow:

Given an area of land will be used to grow agricultural crops for j years. At the start of every *m*th decision or planning interval (each lasting d years) where $m = 1, 2, \ldots, M$, the land owner could decide whether to retain the trees for another d years or to replant with new trees. This involves the following variables:

(1) $C_{r,\,m}$ = the amount of carbon released when clearing the trees at planning interval m;
(2) $C_{i,\,m}$ = the incentive from the government to reduce carbon emission during planning interval m;
(3) $C_{c,\,m}$ = the amount of net carbon captured at planning interval m;
(4) $C_{cum,\,m}$ = the cumulative amount of net carbon stored over the years of interval m.

For simplicity, net carbon captured is used rather than separately representing the carbon captured and carbon released.

3. Dynamic programming model for plantation planning

The problem was solved using the *backward procedure* of DP. A detailed tutorial of this method for cases with discrete stage-wise choices is available in many textbooks (e.g., Bertsekas, 1995). In this work, the relationship between *stages* and *time* can be summarized as in Fig. 1. The stage number is denoted by $n = 1, 2, \ldots, N$. The first stage indicates the end of period for land usage designated by j ($= m \times d$) years. By moving backwards, the stage number increases by an increment of 1, while the time decreases by increments of d. If this were to be viewed from the forward