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Using Virtual Options to Turn "CO_2lonialism" into "Clean Development"

Urvashi Narain and Klaas Van 't Veld

1616 P St. NW
Washington, DC 20036
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RESOURCES
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USING VIRTUAL OPTIONS TO TURN "CO_2LONIALISM" INTO "CLEAN DEVELOPMENT"

Urvashi Narain

Resources For the Future

Klaas van 't Veld

Department of Economics and Finance, University of Wyoming

Abstract

It is widely recognized that industrialized countries' commitments under the Kyoto Protocol to reduce their greenhouse-gas emissions will be far less costly to achieve if they can be met at least in part through investment in cheap abatement options available in developing countries. Developing countries have been reluctant to permit such investment, however, out of concern about the so-called "low-hanging fruit problem." The standard characterization of this problem is that if developing countries allow their cheap abatement options to be used now, they may find themselves worse off in future when they take on emissions-reduction commitments of their own, because only expensive abatement options will remain. We show that under plausible CDM-market imperfections a low-hanging fruit problem may indeed arise, but that the standard characterization of the problem is incorrect. We also propose a simple solution, based on mandating a "virtual" option clause in CDM-investment contracts.

1. Introduction

The Kyoto Protocol on climate change includes several flexibility mechanisms aimed at reducing the global cost of greenhouse-gas abatement. One of these is the Clean Development Mechanism (CDM), which allows industrialized countries that commit to emissions reductions under the treaty (so-called Annex-1 countries) to meet part of their commitment by investing in projects that reduce net emissions of CO_2 and other greenhouse gases in developing countries.[1] It is widely agreed that the CDM will significantly reduce the Kyoto Protocol's costs, by allowing Annex-1 countries to tap into the large pool of relatively cheap abatement options available in developing countries. The size of this pool is indicated, for example, by Jotzo and Michaelowa's (2002) estimate that industrialized countries (excluding the United States) will choose to meet about one-third of their total emissions-reduction commitments of 1.2 Gt CO_2/year through CDM projects, slightly exceeding the estimated fraction they will choose to meet through domestic abatement.[2]

In order for these cost savings to be realized, however, Annex-1 countries will have to address a concern known as the "low-hanging fruit" problem (also sometimes referred to as the "cherry picking," "cream skimming," "eco-colonialism," or even[3] "CO_2lonialism" problem), which has led many developing countries to question whether hosting CDM projects would in fact be in their own best interests. The standard characterization of this problem is that if developing countries allow their cheap abatement options to be used now, they may find themselves worse off in future when they take on emissions-reduction commitments of their own, because only expensive abatement options will remain.[4]

[1] The other two flexibility mechanisms are the Joint Implementation (JI) mechanism, which would allow Annex-1 countries to get credit for emissions reductions achieved in other Annex-1 countries, and the creation of a market for carbon emissions credits.

[2] Credit purchases from economies in transition (EIT) countries such as Russia and the Ukraine, as well as some JI projects, account for the remainder.

[3] See, e.g., FERN (2000).

[4] The issue of the low-hanging fruit problem has been raised by a number of developing countries in a number of different forums. In September of 1998, for example, 70 experts from different parts of Africa gathered in Accra, Ghana to discuss how best to prepare their countries for CDM, and raised the issue of the low-hanging fruit problem (Accra, 1998). More recently, in June of 2004 at a workshop on Crucial Issues in CDM held in Bangkok, Thailand, the director of a Thai NGO, Dr. Surachet Tamronglak, stated that "Thailand is cautious before jumping into CDM with concerns over the low-hanging fruit issue (Bangkok, 2004)." A broader reference to the low-hanging fruit problem appears in the Third Assessment Report of the Intergovernmental Panel on Climate Change, which notes in its discussion of equity and global climate policy that the low-hanging fruit problem is an issue raised by critics of the CDM (Banuri and Weyant, 2001). Similarly, a note prepared by the Prototype Carbon Fund facility of the World

The formal economic literature on the low-hanging fruit problem is very small. Rose, Bulte and Folmer (1999) cast the low-hanging fruit problem as analogous to the increase in extraction costs that may result when an exhaustible resource is depleted over time. To the extent that the cheapest carbon-abatement[5] projects in a developing country are undertaken ("extracted") by Annex-1 investors, the future abatement costs of the country will increase, because it will have to rely on the more expensive projects that remain at the time when it takes on emissions-reduction commitments of its own. A low-hanging fruit problem exists in Rose et al.'s model if the country is not compensated for this future cost increase, the present value of which is effectively a scarcity rent of unused projects. A more recent paper by Akita (2003) considers potential benefits from technological transfers by Annex-1 countries that might offset the low-hanging fruit problem. Lastly, Bréchet, Germain and van Steenberghe (2004) consider the possibility that the host country's future emissions-reduction requirement may become more stringent if it decides to participate in the CDM, thereby worsening the low-hanging fruit problem.

All three studies beg the question, however, why the low-hanging fruit problem would arise in the first place. It is this question that our paper focuses on. Clearly, if CDM-market conditions are perfect, no low-hanging fruit problem can arise: allowing CDM investment will not make host countries worseoff in future, because their governments will fully anticipate both the direct and indirect opportunity costs of hosting any CDM project, and will demand full compensation for both. We argue in this paper, however, that under plausible imperfections of the CDM market, a low-hanging fruit problem may very well arise. Specifically, it is not implausible that developing-country governments, or their representatives in negotiations with Annex-1 investor may be ill-informed or (for reasons to do with political instability and corruption) more impatient than their citizens. If so, they may sell off CDM projects at suboptimally low prices, or suboptimally soon, thereby potentially leaving their citizens worse off in future than they would have been in the absence of the CDM.[6]

Bank to address host-country concerns in climate-finance deals points out that the low-hanging fruit problem is a concern that has been voiced by many CDM countries (World Bank, 2003).

[5]Hereafter, we use the term "carbon emissions" as shorthand for emissions of any greenhouse gases regulated under the Kyoto Protocol, and "carbon abatement" as shorthand for abatement of any such emissions.

[6]Arguably, some analysts who have warned of the low-hanging fruit problem in fact had this type of problem in mind, without articulating the implicit assumptions about government behavior that give rise to it.

We start by showing that the low-hanging fruit problem takes on a different form if, consistent with the institutional reality of the Kyoto Protocol, carbon-credit markets are in place at the time—commonly referred to as "graduation"—when a host country takes on emissions-reductions commitments of its own. Contrary to Rose et al.'s (1999) result, which relies on the absence of credit markets, the indirect opportunity cost of hosting cheap CDM projects—in addition to any direct costs of the projects themselves—no longer arises from the host-country government's having to use more expensive projects after graduation. Rather, it arises from no longer being able to reap potential profits from the project—credit revenues less direct project costs—after graduation. Put differently, allowing an Annex-1 investor to undertake a cheap project under the CDM destroys host-country government's option of undertaking the project itself after graduation; the indirect opportunity cost is equal to the present value of this destroyed option. If the host country is not compensated for this forgone value, it may find itself worse off with the CDM than without, and in this sense a low-hanging fruit problem can be said to arise.

This clarification of the precise nature of the low-hanging fruit problem in the presence of credit markets suggests a quite straightforward contractual solution. The can be prevented by simply including in every contract for a CDM project a mandatory clause specifying that the host country retains an option to at some future time undertake the project "virtually" as opposed to physically. Excercising this option involves paying the Annex-1 investor whatever it would have cost to undertake the project physically at that future time. In return, the host country receives a stream of carbon credits equivalent to the stream of credits it would have earned had it undertaken the project at that future time.

This virtual-option clause could take one of two forms, which by analogy to financial options we call "European" and "American." The European clause would allow exercise of the option only at a fixed time, namely the time of the host country's graduation. In contrast, the American clause would allow exercise at any time up to the time of graduation, which we show yields additional benefits in terms of ensuring optimal timing of CDM projects and full rent extraction by the host country. Crucially, however, for the American clause to yield these benefits, the host-country government must be able to detach the rights conferred by the clause from the CDM contract and transfer them to third parties; that is, the virtual option must be tradeable.

Existing CDM instutions can be used to make this solution workable in practice. In particular, institutions are already in place to address the very different, "additionality" problem associated with the CDM. Because the CDM is not a cap-and-trade program, there is a risk that it may end up increasing overall greenhouse-gas emissions, namely if Annex-1 investors were to receive carbon credits for undertaking CDM projects that the host-country government would have undertaken anyway. Only if projects are "additional," in the sense that they would not be profitable to the host country without the additional revenues from carbon credits generated, will awarding those credits to Annex-1 investors leave overall emissions unchanged. Verifying additionality requires an independent assessment of both the costs of undertaking CDM projects and the number of credits that they are likely to generate. But such an independent assessment is precisely what is needed also to determine the terms at which our proposed virtual-option clause would be exercised, suggesting that the solution to the low-hanging fruit problem can "piggy-back" on the solution to the additionality problem.

The remainder of the paper is organized as follows. Section 2 develops a simple discrete-time model to show that if credit markets are in place at the time of a host country's graduation, its indirect opportunity cost of selling off cheap CDM projects is different from that described under the standard characterization of the low-hanging fruit problem. Section 3 lays out our argument for why, even though no low-hanging fruit problem could arise under perfect CDM-market conditions, a low-hanging fruit problem may well arise given plausible market imperfections. Section 4 introduces our virtual-option solution to the problem. Section 5 extends our argument to continuous time. Section 6 discusses some additional extensions, and Section 7 concludes.

2. The low-hanging fruit problem as commonly characterized

In this section, we develop a simple discrete-time model of foreign investment in CDM projects to characterize the opportunity cost to a developing country of hosting such investment.

2.1. *The two-period model*

Consider a two-period model in which period 0 represents the time (years, possibly decades) until a developing country is expected to graduate, i.e., commit to reducing its carbon emissions under a climate-change agreement. Period 1 represents the time from graduation onwards. Let E^t denote the target level of emissions to which the country is committed to reduce its period-1 emissions, before any emissions trading. Graduation will allow the country to participate in a global carbon-credit market, however, so that it can buy $E - E^t$ credits if its actual emissions E exceed E^t, or sell $E^t - E$ credits if its actual emissions fall short of E^t. Let p denote the price of such credits in period 1, and assume the country is sufficiently small that it treats this price as given. Assume also initially that p is unchanged from its level in period 0, during which emissions targets and a credit market are in place only for Annex-1 countries.

The developing country starts out at the beginning of period 0 with a set of projects that can potentially be undertaken to reduce carbon emissions. Each such project requires an initial investment I and then abates q units of carbon over the project's lifetime L, which for simplicity we set equal to one period for all projects. The levels of I and q vary across projects, and arranging the projects in order of increasing per-unit abatement cost I/q yields the country's effective marginal abatement cost curve in period 0.

The country faces a decision whether or not to permit CDM investment in these projects by Annex-1 countries during period 0. To keep the exposition maximally simple, we assume that if the country chooses *not* to permit such investment, it will find itself at the beginning of period 1 with the same set of projects as it started out with at the beginning of period 0, and therefore the same marginal abatement cost curve.

[Figure 1 about here.]

The curve labeled $MAC_n(A)$ (subscript n for "no CDM") in panel (a) of Figure 1 represents this marginal abatement cost curve at the beginning of period 1, where abatement A is measured from left to right on the horizontal axis and emissions E are measured from right to left. The abatement level A^t is that which would reduce the country's emissions from its level $E^{\max}$ in the absence of abatement to the target level E^t committed to under the terms of its graduation. Given that a cap-and-trade system is in place in period 1, we can imagine the country receiving an endowment of E^t carbon credits at the beginning of that period. Standard arguments then imply that, given the credit price p, the country will optimally abate up to level A^*, at a total cost of $TAC_n(A^*) = \int_0^{A^*} MAC_n(A)\,dA$, and will earn revenues of $p(A^* - A^t)$ from selling its excess endowment of $A^* - A^t = E^t - E^*$ credits on the market. Letting C_n denote the net cost to the country of complying with its emissions commitment if it does not participate in the CDM, we therefore have

$$C_n \equiv TAC_n(A^*) - p(A^* - A^t).$$

Consider next how the situation changes if the country chooses instead to permit CDM investment in period 0, and if we assume that any projects undertaken by Annex-1 investors during that period 0 are no longer available in period 1. Suppose in particular that the country agrees to host CDM projects *at cost,* i.e., without receiving any compensation over and above that needed to cover the projects' direct investment cost I. Under this assumption, Annex-1 investors will during period 0 invest in all projects with per-unit abatement costs I/q up to p. As a result, the host country's marginal abatement cost curve $MAC_c(A)$ at the beginning of period 1, obtained by arranging all *remaining* projects in order of increasing per-unit abatement costs, is just the $MAC_n(A)$ curve truncated at A^*. The resulting picture, shown in panel (b) of Figure 1, appears to support the standard characterization of the low-hanging fruit problem: by agreeing to host CDM projects, the country finds itself at graduation with only expensive abatement options left to meet its abatement requirement A^t.

What the standard characterization ignores, however, is the presence of the market for carbon credits. Given our assumptions that the country's decision whether or not to participate in the CDM does not affect the credit price p, the country will in fact meet its abatement requirement without using *any* of its expensive abatement options. Instead, it will buy A^t credits on the market, at a total cost of

$$C_c \equiv pA^t.$$

The net opportunity cost to the country of hosting CDM projects (apart from the direct investment costs I for which the host country is by assumption fully compensated by Annex-1 investors) is therefore

$$C_c - C_n = pA^* - TAC_n(A^*).$$

Note that this opportunity cost just equals the aggregate profits that the country could have earned from all the projects undertaken by Annex-1 investors, had it instead undertaken these projects itself after graduating. Equivalently, the net opportunity cost to the country from hosting the CDM projects (again, apart from the up-front investment costs I) is just the value of the option to delay those projects until graduation time. This result, which underlies much of the analysis in the remainder of this paper, holds quite generally. In particular, the result in no way depends on our simplifying assumptions fixing (i) the credit price p; and (ii) the marginal abatement curve. Both may change over time without affecting the result, and in fact may change either deterministically or stochastically. Nor does the result depend on our assumption, implicit in Figure 1, that the host country is a net seller in the credit market after graduation if it does not participate in the CDM.

Intuitively, given that a carbon-credit market is in place, and provided any changes over time in the model parameters—including the host country's anticipated graduation time and subsequent abatement requirement—are exogenous to the country's decision whether to participate in the CDM,[7] its opportunity costs of CDM participation can, and in fact should, be evaluated purely on a project-by-project basis. Specifically, under these assumptions all possible states of the world post-graduation with respect to any given CDM project that the host country might consider selling to an Annex-1 investor can be partitioned into just two relevant classes. One class consists of those states of the world in which, after undertaking any still available projects that it finds profitable to undertake post-graduation, the host country would either not have wanted to or no longer be able to additionally undertake the CDM project in question. [8]In such states of the world, the host country will by definition not have incurred any opportunity cost from having sold away the project under the CDM. The other class consists of those states of the world in which the host-country government *would* have wanted to additionally undertake the CDM project, whether to help meet its abatement obligations or to exceed them. In the former case, it will now have to buy any credits

[7] Whether participation in the CDM may in reality affect a host country's graduation time or subsequent abatement requirements is impossible to assess at this point, since graduation criteria and terms have yet to be formally discussed (let alone agreed upon) in the context of climate negotiations. As for future credit prices and abatement-technology parameters, these can reasonably be assumed exogenous to a country's CDM decisions as long as the country's potential supply of CDM projects is "small" relative to the total market.

[8]The first case could arise, for example, if the price of carbon credits had declined in the meantime to a point where the specific project would no longer be profitable; the second case would arise for projects that are inherently "perishable," such as projects that prevent deforestation (were these to become recognized under the CDM), or inherently short-term, such as projects that increase the use of short-lived energy-saving appliances. Section 6 provides further discussion of the importance of project lifetimes to the low-hanging fruit problem.

that the project would have generated; in the latter case, it will no longer be able to sell those credits. Either way, the *opportunity* cost of having sold away the project consists of the value of the credits that it would have generated less the avoided cost of undertaking the project, i.e., of the profits that the project would have generated. But then it follows that, after aggregating over all states of the world in both classes and discounting to the beginning of period 0, the opportunity cost of selling away a project under the CDM exactly equals the expected present value of an option to delay that same project until period 1.

In the policy debate on the low-hanging fruit problem, these implications to the CDM of the existence of a credit market appear to have been missed entirely. Once they are grasped, it is immediate that the standard characterization of the low-hanging fruit problem is incorrect: in the presence of a credit market, there is simply no issue of "having to abate expensively rather than cheaply" if cheap projects are sold away—the credit market eliminates any such spillover effects between decisions with respect to individual projects. For the same reason, arguments made, e.g., by then Deputy Secretary of the U.S. Treasury Larry Summers (1999)), reassuring developing countries that technological progress or growth will add new, cheap abatement projects over time, thereby supposedly mitigating the low-hanging fruit problem, are beside the point. So are various solutions to the problem that have been suggested, such as limiting investment in CDM to relatively expensive projects (Gupta and Bhandari, 2000); treating the Annex-1 investor's avoided domestic abatement projects as the baseline for CDM crediting (Dessus, 1998); putting a cap on the time period for which Annex-1 investors can receive credits (Hanafi, 1998; Read, 1998); or forcing Annex-1 investors to share with the host country some fraction of the credits generated, which the host country can then bank and sell after graduation (Accra, 1998; World Bank, 2003). All of these supposed solutions would inefficiently reduce the set of projects undertaken under the CDM, without guaranteeing that the host country's compensation for the remaining projects will cover their full opportunity cost.

An even more basic point that has not received much attention in either the policy debate or the formal economic literature[9] is that *under perfect CDM-market conditions,* no solutions to the low-hanging fruit problem are needed in the first place, because no low-hanging fruit problem will ever

[9] An exception in the legal literature is Wiener (1999).

arise: any host-country government negotiating a CDM contract will be fully aware of the option value of delaying the CDM project until graduation, and will not agree to sell away the project unless the negotiated price covers both the immediate investment cost and this option value.

That said, few analysts familiar with institutional realities in developing countries would dispute that market conditions in such countries are often highly *im*perfect, in ways that may well lead host-country governments to undervalue the option of delaying CDM projects. It is not at all implausible, for example, that a host-country government might be less well-informed than its Annex-1 investor counterparts about any number of factors that might affect the value of delaying a CDM project, such as future changes in abatement technologies, or changes in market conditions that might affect future credit prices. As a result, the host-country government may well underestimate the value of delay. Nor is it implausible, given the prevalence of corruption and political instability in developing countries, that a host-country government might be more impatient than the citizens on behalf of which it negotiates. If the government expects to reap private benefits from projects only as long as it is in power, it will overdiscount the value of projects undertaken in future relative to that of projects undertaken immediately.

In both cases, participation in the CDM may give rise to a low-hanging fruit problem, in the sense that at least some range of CDM projects may be contracted out to foreign investors at a price that does not compensate for the projects' full opportunity cost. If so, then with respect to these projects, host country citizens will by definition find themselves worse off ex post, since these projects would have yielded higher profits had they been retained until graduation.

3. The case for the existence of a low-hanging fruit problem

To illustrate the low-hanging fruit problem in the presence of credit markets formally, consider a slight generalization of the model that allows for deterministic changes over time in the credit price p and in the technology parameters I and q for each project. Let p_t, q_t, and I_t denote the respective values of the latter variables in period $t \in \{0, 1\}$. Also, let $V_t = \max[p_t q_t - I_t, 0]$ denote the value of undertaking a given project in period t.

Using this model, we can then define the low-hanging fruit problem as arising whenever the equilibrium level of compensation for a CDM project negotiated by the host-country government in period 0 exceeds the immediate cost I_0 by less than the discounted value $V_1/(1+r)$ of the option to delay the project until period 1.

The first potential reason for the low-hanging fruit problem discussed above, namely underestimation by an ill-informed host-country government of the value of delaying a project, can be modeled by assuming that the host-country government values the option to delay at $\delta V_1/(1+r)$, where $\delta < 1$. That is, an ill-informed host-country government applies the correct discount factor $1/(1+r)$ to the value of the project at time 1, but perceives this value to be δV_1 instead of V_1. Such underestimation might result because the host-country government overestimates I_1, or underestimates p_1 or q_1.[10]

To model the second potential reason for the low-hanging fruit problem discussed above, namely overdiscounting by a corrupt government, we need to be specific about the nature of the private benefits that the government derives from projects, and the nature of the political uncertainty that induces it to discount the benefits it expects to derive from projects undertaken in future.[11]

Initially (until Section 6), we rule out corruption in the form of soliciting of bribes by government officials, or diversion of project profits for private ends; that is, we assume that even a corrupt government passes on all profits from CDM projects to the citizens it represents. The private benefits it derives instead take the form of non-monetary, "patronage" benefits—political kudos, for example, from its ability to allocate the public projects (schools, hospitals, roads) financed by these profits to favored constituents or firms. To keep the model maximally simple, we assume that the government cares *only* about these private benefits, that these benefits are proportional in size to the project profits, and that they accrue concurrently with the profits. Moreover, we assume that patronage does not occur on a scale sufficient to affect (positively or negatively) the government's probability of staying in power, so that we can treat this probability as exogenous. Provided this

[10]An ill-informed host-country government may of course also *over*estimate V_1 and hence demand too much compensation. If so, it may not find any buyers of the project in period 0, but obviously, even if it does, no low-hanging fruit problem will arise. Hereafter, we ignore this case.

[11]It need in fact not be the host-country government itself that is corrupt; as noted by Michaelowa and Dutschke (2002), the negotations process over CDM projects may also be captured by rent-seeking interest groups within the country. As long as there is uncertainty over whether such capture will persist, the arguments of our paper will go through.

probability is less than one, and the government expects to reap private benefits from projects only as long as it is in power, it will overdiscount the value of projects undertaken in future relative to that of projects undertaken immediately.

With these assumptions, we can treat a corrupt host-country government as accurately perceiving the value of delaying a project until time 1 to be V_1, but applying discount factor $\delta/(1+r)$ to this value rather than $1/(1+r)$, where $\delta < 1$ is its perceived probability of remaining in power.[12]

For both underestimating and overdiscounting host-country governments, then, we have that the host-country government's reservation price for the CDM project will be too low, namely equal to $I_0 + \delta V_1/(1+r)$ rather than $I_0 + V_1/(1+r)$. Of course, this in itself need not imply that the *actual* price negotiated is too low as well. Whether a low-hanging fruit problem in fact arises for a given CDM project depends on two additional factors, namely (i) whether the Annex-1 investor has any market power, (ii) whether the project is expected to increase in value from time 0 to time 1, and (iii) whether the Annex-1 investor can contract with host-country government at time 0 to undertake the project at time 1.

The importance of the first factor is self-evident. In the extreme case where the host-country government faces a single, monopsonist Annex-1 investor, the negotiated price for each project will be driven down to the host-country government's, by assumption too low, reservation price, and a low-hanging fruit problem will therefore arise for *all* CDM projects that are undertaken. As for the second and third factors, consider a project whose value increases sufficiently over time for the condition $V_0 < V_1/(1+r)$ to hold. Such a project should optimally not be undertaken under the CDM, at time 0, but should instead be delayed until time 1, since the present value of delaying the project exceeds that of immediately undertaking it. Suppose, however, that the host-country government perceives the value of delay to be only $\delta V_1/(1+r)$. In this case, even if Annex-1 investors have no market power, so that the host-country government would capture the full value V_0 from selling off a contract to undertake the project at time 0, a low-hanging fruit problem may still arise if V_0 exceeds $\delta V_1/(1+r)$, because the host-country government will then want to sell the project off too soon.

[12]Overdiscounting of V_1 might also occur if an ill-informed host-country government overestimates the rate of interest r. Hereafter we ignore this case, since it overlaps with the other two in obvious ways.

Whether a low-hanging fruit problem will in fact arise depends on the third factor, however. If Annex-1 investors can contract with the host-country government at time 0 to undertake the project at time 1, competitive bidding between the Annex-1 investors will drive up the price of such a contract to its full value $V_1/(1+r)$. Provided the contract specifies up-front payment of this amount, even an overdiscounting host-country government will prefer it to a contract worth V_0 for immediate undertaking of the project. As a result, the project will in fact be optimally delayed, and no low-hanging fruit problem arises.

There are several reasons, both economic and political, for being skeptical about the real-world relevance of such contracts for CDM investment in the potentially far future, however. First, if the contract price is indeed to be paid up front, there is a risk of hold-up problems that would make the contract less attractive to Annex-1 investors. The scope for such problems is likely to be greater, the further into the future the actual starting date of the project.

Second, given real-world uncertainty about future carbon prices and project costs, the optimal (joint-surplus maximizing) contract would take the form of what might be called a "real option" contract, leaving the decision whether and when to undertake the project up to the Annex-1 investor. In practice, such open-ended contracts between governments and private firms are rarely observed, particularly when the expected optimal exercise time of the real option lies far into the future. Government contracts with private firms to develop oil or gas fields, for example, commonly take the form of leases with fairly short expiration times, on the order of five to ten years; the right to develop a field reverts to the government if left unexercised by this time. In a paper that uses a real-option approach to analyze such contracts, Bjerksund and Ekern (1990) note moreover that in some countries the government retains the right to approve any field development plans, including the timing. They speculate that "[f]or macroeconomic planning purposes, it may be important for the government to have the corporate development activities fit into a socially desired activity pattern."

The issue of retaining government control looms especially large in the CDM context, given developing countries' fear of undue foreign influence on their domestic affairs and potential loss of hard-fought sovereignty. Common references to the CDM as a form of "eco-" or "carbon colonialism" draw parallels to the countries' negative experiences in colonial times with open-ended, lopsided concession contracts granted to foreign oil and mining companies. In face of this rhetoric, it hard to believe that host-country governments would be willing (or politically able) to cede to Annex-1 investors the degree of control implicit in real-option contracts.[13]

Although it may be possible to devise variants of real-option contracts that avoid these obstacles, analyzing this issue is beyond the scope of this paper. Hereafter, we simply assume that real-option contracts are infeasible, and that all CDM contracts commit the Annex-1 investor to undertake the project in question immediately.[14]

4. A simple solution for the low-hanging fruit problem

The analysis of the low-hanging fruit problem in the previous section suggests a very simple solution: include in every CDM contract a clause to the following effect:

> The host-country government retains the right to undertake this project 'virtually' at the time of graduation, by replicating, through monetary transactions between the Annex-1 investor and the host-country government, the revenues and costs that would have accrued to the host-country government had it undertaken the project *physically* at graduation.

In the simple context of our two-period model, the clause could, if exercised at time 1, be implemented quite easily, by having the Annex-1 investor transfer to the host-country government q_1 credits worth p_1—the q_1 credits that the host-country government would have earned had it physically undertaken the project at time 1—in exchange for a payment by the host-country government to the Annex-1 investor of I_1—the cost that the host-country government would have incurred. In practice, however, changes over time of project costs and abatement technologies imply that implementing the clause would require verifiable estimates of what the project would have cost at time 1 and the number of credits that it would have generated. As discussed in the introduction,

[13]It is not only developing countries that are suspicious of foreign investment. In the U.S., surging Japanese investment in U.S. real estate, golf courses, movie studios, etc., in the late 1980s drew forth similar rhetoric. More recently, a bid by the Royal Dutch/Shell Group to take over Australia's largest energy company, Woodside, was vetoed by the Australian government as being contrary to the national interest. The New York Times of April 24, 2001 noted that

> "Foreign ownership is a sensitive issue in Australia, which needs to attract international development and capital but fears becoming what the prime minister, John Howard, has called 'a branch office economy' if too many significant domestic assets fall into foreign hands."

[14]It should be noted also that real-option contracts, even if they were feasible, would not solve any low-hanging fruit problem that arises from market power on the part of the Annex-1 investor, i.e, from factor (i) above. Contrary to the virtual-option solution discussed in the next section, real-option contracts would not increase the level of competition faced by Annex-1 investors and, consequently, would not prevent the host country from being pushed to a too low reservation price.

CDM institutions that must be in place anyway to ensure that projects are "additional" should be able to provide such estimates.

Note that the virtual-option clause prevents the low-hanging fruit problem essentially *by definition*: given that we defined the low-hanging fruit problem as arising whenever the host-country government receives less compensation than the profits it would have earned had it undertaken the project itself at graduation, a contractual clause that in effect mandates that minimum level of compensation must necessarily prevent the low-hanging fruit problem.

More specifically, when the source of the low-hanging fruit problem is market power on the part of the Annex-1 investor, which drives the price for the CDM contract down to the host-country government's too-low reservation price $\delta V_1/(1+r)$, the virtual-option clause works by in effect pre-committing the host-country government to a reservation price worth $V_1/(1+r)$ when discounted to time 0. Alternatively, when the source of the low-hanging fruit problem is suboptimal timing of the project by the host-country government, the clause works because, even though the host-country government may still at time 0 misperceive the future payment $V_1/(1+r)$ due to it, and may therefore be willing to sell off a project with value $V_0 < V_1/(1+r)$ that should optimally be undertaken at time 1, no Annex-1 investor will bid on such a project; Annex-1 investors will realize that even the maximum value V_0 that they might obtain in exchange for undertaking such a project at time 0 (namely if they buy the project at cost I_0) will not make up for the present value $V_1/(1+r)$ of the liability they incur.

There are, however, a number of drawbacks to this proposed solution that become apparent only if we generalize our model to continuous time. The next section analyzes these drawbacks and shows how the virtual-option clause can be modified to overcome them.

5. The low-hanging fruit problem in continuous time

To convert the model to continuous time in the simplest way possible, we initially assume that any abatement project, if undertaken at time T at initial investment cost $I(T)$, thereafter reduces emissions at a constant flow *rate* of $q(T)$. Although both $I(T)$ and $q(T)$ may change over time, for instance because of technological progress, we assume they are locked in at their time-T values once the project has been initiated.[15] [6 we also assume for simplicity that all projects are infinitely lived ($L = \infty$). The price of carbon is assumed to increase deterministically over time at exponential rate α, i.e., at any given time t we have $p(t) = p(0)e^{\alpha t}$, where $p(0)$ is the price at time 0, when the CDM market is first established. Throughout, we assume that the rate of price increase α is strictly positive, but smaller than the social discount rate r.[16]

Given these assumptions, the current value of undertaking a CDM project at time T when future credits are discounted at rate r is[17]

$$V(T) \equiv \int_T^{\infty} e^{-r(s-T)} p(0) e^{\alpha s} q(T)\, ds - I(T) = \frac{p(0)q(T)}{r-\alpha} e^{\alpha T} - I(T). \tag{1}$$

An important assumption that will be maintained throughout the remainder of the paper is that the *present* value $e^{-rT}V(T)$ of undertaking any CDM project is a single-peaked function of T, so that there is a unique locally and globally optimal time T^* to undertake the project:

$$T^* \equiv \arg\max_{T \geq 0} e^{-rT} V(T). \tag{2}$$

It will be useful at times to consider the special, "benchmark" case of the model that arises if the actual (but not necessarily the perceived) paths of $q(T)$ and $I(T)$ are constant, so $q(T) = q$ and $I(T) = I$. It is easy to check that in this case $e^{-rT}V(T)$ is in fact single-peaked, achieving a maximum at $T^* = \max\{(1/\alpha)\log[rI/p(0)q], 0\}$.

It will be useful also to categorize CDM projects into three types, depending on their value of T^*. Projects for which $T^* = 0$, implying that they should optimally be undertaken immediately, will be labeled Type I. Projects for which $T^* \in (0, G)$, where G is the time at which a host country is expected to graduate, will be labeled Type II. These are projects that should optimally be undertaken under the CDM, but not immediately at time 0. Finally, projects for which $T^* \geq G$ will be labeled Type III. These are projects that should optimally be delayed until time G or after, and should therefore *not* be undertaken under the CDM.

[15] That is, we assume that abatement capital is "putty-clay."

[16] The assumption that α is positive is motivated by Pearce et al.'s (1996) review of integrated assessment models that estimate how marginal damages from carbon emissions should evolve over time under an economically efficient climate policy. All studies reviewed find that marginal damages should increase over time, at rates that vary from 1.5% to 4% per year. The implication is that, if one believes that future climate negotiations will seek to implement an efficient policy, one should expect carbon prices to increase at roughly these rates. The assumption that α is smaller than r ensures that the value of projects is finite.

[17] By writing this value in the form $V(T) = X$ rather than $V(T) = \max[X, 0]$, we are implicitly restricting attention to projects with non-negative values at all T, thereby abstracting from the possibility that $q(T)$ may fall or $I(T)$ increase so much that $V(T)$ becomes negative.

A final set of assumptions concerns host-country government's expectations at any time T about the value of delaying a project until some later time $T+t$, possibly after graduation. Given that graduation in some sense marks a host country's transition from developing to industrialized status, it is reasonable to assume that the country will by then be able to either finance projects itself or attract sufficient interest from foreign investors to face a competitive market for contracting out abatement projects. If so, then the host-country government will expect to receive the full value of credits generated by the project. Although in reality the transition to a competitive market will of course be gradual, we simplify by assuming that in the monopsony case it takes place abruptly at time G; that is, we assume that the host-country government faces a monopsonist Annex-1 investor all the way up until graduation, after which the market suddenly becomes competitive. As a result, the only delay times $T+t$ relevant to the host-country government are those at or after G, since it will have no control over project timing before G. In the competitive case, in contrast, any delay time $T+t$ is relevant, because it is the host-country government that chooses when to auction off the project.

We assume that an ill-informed host-country government will perceive the present value of delaying a project until any such relevant delay time to be only $e^{-rt}\widetilde{V}(T+t)$, where $\widetilde{V}(T+t) < V(T+t)$. Such underestimation might result, for example, because the host-country government underestimates the rate at which $I(T)$ will fall over time, or the rate at which $q(T)$ will increase. To simplify further, we specify that $e^{-rt}\widetilde{V}(T+t) = e^{-rt}e^{-\delta t}V(T+t)$. That is, the degree of underestimation of $V(T+t)$ increases at constant exponential rate δ in the distance t from the time of estimation.

As for a corrupt host-country government's perceptions about the value of delay, we assume that such a government is uncertain at any time T about its prospects of staying in office, and this uncertainty takes the form of a constant probability $\delta\, dT$ of a "government overthrow" event during the next time interval of infinitesimal length dT. If this event occurs, it will put an end to the government's ability to enjoy private benefits from abatement projects.[18] We continue to assume that these private benefits are all that a corrupt goverment cares about, and that these benefits are proportional in size to, and accrue concurrently with, the project's profits. Given these assumptions, the host-country government will perceive the present value of delaying a project until

[18]Note the potentially confusing switch in notation from Section 3, where we defined δ as the probability of a corrupt host-country government *staying* in power.

a relevant $T+t$ to be $e^{-rt}e^{-\delta t}V(T+t)$; that is, the arrival rate δ of overthrow events effectively increases the host-country government's discount rate from r to $r+\delta$.

The special assumptions involving the parameter δ are made purely for analytical convenience. Specifically, they serve two purposes. First, they make explicit mathematically the essential equivalence of underestimation and overdiscounting for the potential existence of a low-hanging fruit problem. Second, because they involve constant exponential "decay" rates of future payoffs, they ensure that host-country government decisions are time-consistent.

5.1. *The low-hanging fruit problem in the monopsony case*

Consider now first the case where the host-country government faces a monopsonist Annex-1 investor. Key to the low-hanging fruit problem is then the host-country government's reservation price for allowing the Annex-1 investor to undertake a project under the CDM, i.e., at some time $T<G$, and how this reservation price compares to the value of the project to the host country's citizens were the project undertaken instead at $T \geq G$.

By our assumptions above, the host-country government's reservation price is for both an underestimating and an overdiscounting host-country government given by

$$e^{-(r+\delta)(T^g-T)}V(T^g),$$

where T^g is the host-country government's perceived optimal time of auctioning off the project at or after G:[19]

$$T^g \equiv \arg\max_{T\geq G} e^{-(r+\delta)T}V(T). \tag{3}$$

Given this reservation price, the Annex-1 investor will choose to undertake a project at a time T^m (m for "monopsony") that maximizes the present value of its rents. That is,

$$T^m \equiv \arg\max_{T\in[0,G)} e^{-rT}[V(T) - e^{-(r+\delta)(T^g-T)}V(T^g)], \tag{4}$$

subject, of course, to the constraint that those rents are non-negative at T^m.

A third critical value of T that will be useful in the analysis that follows is

$$T^c \equiv \arg\max_{T\geq 0} e^{-(r+\delta)T}V(T). \tag{5}$$

[19] More precisely, an underestimating host-country government will be indifferent between undertaking the project itself at T^g or auctioning it off to a foreign investor. An overdiscounting host-country government, in contrast, will strictly prefer auctioning off the project for an up-front payment of the project's value, since undertaking the project itself and earning credit revenues only over time would put its private benefits at risk.

Just as we assumed that the function $e^{-rT}V(T)$ is single-peaked, we will assume that the function $e^{-(r+\delta)T}V(T)$ is single-peaked as well, and that therefore T^c is unique. Given this assumption, it is not hard to show that for Type-II and -III projects $T^c < T^*$.

Time T^c will play an important role in the next subsection, because it is the time at which the host-country government would auction off an abatement project to Annex-1 investors if it faced a competitive market (hence the superscript c). In the current subsection, T^c turns out to play an important role also, as will become clear from the proof of the following proposition:

Proposition 1. *If the host-country government faces a monopsonist Annex-1 investor, then*

(a) *the Annex-1 investor will undertake not just all Type-I and -II projects, but also some Type-III projects, so that the range of projects undertaken under the CDM will be too large;*

(b) *the Annex-1 investor will undertake the Type-II and -III projects too soon;*

(c) *a low-hanging fruit problem will arise for all projects undertaken by the Annex-1 investor under the CDM.*

Proof: The Type-III projects that the Annex-1 investor will undertake are those for which $T^c < G$ even though $G < T^*$. Since $T^c < T^*$ for all Type-III projects, there must be some for which this is true. Any project with $T^c < G$ will be perceived by the host-country government to be already past its peak value by time G. As a result, it would without the CDM auction off such a project immediately at graduation, yielding value $V(G)$. With the CDM, the host-country government's perceived value at $T < G$ of auctioning the project off at time G will be $e^{-(r+\delta)(G-T)}V(G)$, implying that the Annex-1 investor can profitably undertake at $T < G$ any Type-III project for which $V(T)$ exceeds that perceived value (leaving it with positive rents). The latter condition holds at any $T \in (T^c, G)$. Mathematically, by the single-peakedness of the $e^{-(r+\delta)T}V(T)$ function at T^c, we have that $e^{-(r+\delta)T}V(T) > e^{-(r+\delta)G}V(G)$ for any $T \in (T^c, G)$, and therefore $V(T) > e^{-(r+\delta)(G-T)}V(G)$.

That the Annex-1 investor will undertake these Type-III projects too soon is true by definition: these are projects that should optimally be undertaken after graduation, but that the Annex-1 investor chooses to undertake before, during the CDM phase. To see why it will also undertake Type-II projects too soon, take the derivative of the Annex-1 investor's rents to obtain

$$\frac{d}{dT}\left[e^{-rT}V(T)\right] - \delta e^{\delta T}e^{-(r+\delta)G}V(G). \qquad (6)$$

For all $T \geq T^*$, the first term, and thereby the derivative as a whole, is negative, showing that $T^m < T^*$ for Type-II projects as well. Intuitively, because for all such projects the host-country government's current-value reservation price at any time T, $e^{-(r+\delta)(G-T)}V(G)$, increases with T at rate $r+\delta$, it increases at rate δ in *present* value from the Annex-1 investor's point of view. But then the Annex-1 investor's rents can only be maximized at some time $T < T^*$, where its gross profits $e^{-rT}V(T)$ are also increasing in present value.

Lastly, part (c) of the proposition is an immediate consequence of the host-country government's undervaluation of delayed projects. Because of this, at whatever time T^m the monopsonist Annex-1 investor chooses to undertake a CDM project, the host-country citizens receive only the host-country government's reservation price $e^{-(r+\delta)(G-T^m)}V(G)$. In the absence of the CDM, however, the host-country government would auction the project off at time G, yielding host-country citizens the higher value $e^{-r(G-T^m)}V(G)$ when discounted to time T^m at their own discount rate r. □

5.2. *The low-hanging fruit problem in the perfectly competitive case*

As noted in the previous subsection, in the case where the host-country government faces perfectly competitive Annex-1 investors, it will auction off any abatement project at time T^c defined by condition (5), because its perceived present value $e^{-(r+\delta)T}V(T)$ of doing so then peaks. Whether a low-hanging fruit problem arises then depends on how the value $V(T^c)$ that host-country citizens receive at that time from any project with $T^c < G$, i.e., any project auctioned off under the CDM, compares to the discounted value of what they would receive in the absence of the CDM. From the analysis in the previous subsection we know that, in the absence of the CDM, the host-country government would auction off the project at time G. Discounted to time T^c at the host-country citizens' discount rate r, the present value of their receipts in the latter case would be $e^{-r(G-T^c)}V(G)$. An low-hanging fruit problem therefore arises whenever $V(T^c) < e^{-r(G-T^c)}V(G)$, or equivalently, whenever $e^{-rT^c}V(T^c) < e^{-rG}V(G)$.

This leads to our next set of results:

Proposition 2. *If the host-country government faces perfectly competitive Annex-1 investors, then*

(a) *it will auction off not just all Type-I and -II projects, but also some Type-III projects, so that the range of projects undertaken under the CDM will be too large;*

(*b*) *it will auction off the Type-II and -III projects too soon;*

(*c*) *the low-hanging fruit problem will arise for none of the Type-I projects, only some of the Type-II projects, and all the Type-III projects auctioned off by the host-country government under the CDM.*

Proof: The host-country government will auction off under the CDM any project for which $T^c < G$. This is true of all Type-I and -II projects, as well as exactly those Type-III projects that we showed above will be undertaken by a monopsonist Annex-1 investor under the CDM.

That it will auction of all Type-II and -III projects too soon follows directly from the fact that $T^c < T^*$ for all such projects.

That the low-hanging fruit problem arises for all Type-III projects that are auctioned off, i.e., all Type-III projects with $T^c < G \leq T^*$, follows by the single-peakedness of the $e^{-rT}V(T)$ function at T^*. This single-peakedness implies that the condition for the low-hanging fruit problem identified above, namely $e^{-rT^c}V(T^c) < e^{-rG}V(G)$, holds for all such projects. Moreover, because the condition holds with strict inequality even for the borderline Type-III project, with $T^* = G$, it must by continuity hold also for some range of Type-II projects with T^* sufficiently close to G.

At the other extreme, the low-hanging fruit problem is guaranteed *not* to arise for any Type-I project. For any such project, we have that $0 = T^c = T^*$. Single-peakedness of the $e^{-rT}V(T)$ function at T^* then implies that $V(0) = e^{-rT^c}V(T^c) = e^{-rT^*}V(T^*) > e^{-rG}V(G)$, so that the condition for the low-hanging fruit problem fails. By continuity again, the condition for the low-hanging fruit problem must fail also for some range of Type-II projects with T^* sufficiently close to 0.

For Type-II projects between the two extremes, single-peakedness of the $e^{-rT}V(T)$ function at $T^* \in (0, G)$ implies that $e^{-rT}V(T) \geq e^{-rG}V(G)$ for some interval of times T straddling the peak. Let T^ℓ denote the lower bound of this interval, so T^ℓ is defined implicitly by the condition

$$e^{-rT^\ell}V(T^\ell) = e^{-rG}V(G), \quad T^\ell \neq G. \tag{7}$$

The condition for the low-hanging fruit problem then holds whenever T^c lies before T^ℓ. Whether this is the case for any given Type-II project depends in general on the magnitude of δ. □

5.3. *The virtual-option solution to the low-hanging fruit problem*

None of the complications introduced in the continuous-time model affect either the formulation or the implementability of the mandatory virtual-option clause in CDM contracts that we introduced in Section 4 as a potential solution for the low-hanging fruit problem. We repeat the clause here for convenience:

> The host-country government retains the right to undertake this project 'virtually' at the time of graduation, by replicating, through monetary transactions between the Annex-1 investor and the host-country government, the revenues and costs that would have accrued to the host-country government had it undertaken the project *physically* at graduation.

The only difference with the case of the discrete-time model is that the clause would now be implemented by having the Annex-1 investor transfer not just a single credit at time G, but a stream of $q(G)$ credits forever, in return for a payment of $I(G)$ by the host-country government to the Annex-1 investor. As in the discrete-time case, real-world variability over time of $q(T)$ and $I(T)$—the very variability that potentially gives rise to underestimation errors by the host-country government—would require an independent estimate of $q(G)$ and $I(G)$, but again such an estimate should be readily available from institutions that verify CDM-project additionality.

The following proposition summarizes the incentive properties of the clause in the continuous-time case:

Proposition 3. *Mandating the virtual-option clause in CDM contracts will in the monopsony case*

(a) *induce the Annex-1 investor to undertake only Type-I and -II projects under the CDM,*

(b) *at the optimal time,*

(c) *without any low-hanging fruit problem arising;*

and in the competitive case

(d) *induce the host-country government to auction off only Type-I and -II projects under the CDM,*

(e) *without any low-hanging fruit problem arising.*

Proof: Part (a) follows because the virtual-option clause guarantees the host-country government a payment of $V(G)$ at graduation, or $e^{-r(G-T)}V(G)$ when discounted to any time $T < G$ at which the monopsonist Annex-1 investor might contemplate undertaking the project. This deters the Annex-1 investor from undertaking any Type-III projects, because single-peakedness of the $e^{-rT}V(T)$ function implies that for such projects the gross profits $V(T)$ of undertaking Type-III project at any time $T < G$ would be less than the present value $e^{-r(G-T)}V(G)$ of the future liability that the Annex-1 investor would incur through the clause. In contrast, the Annex-1 investor's net profits remain positive for all Type-I and -II projects.

Part (b) follows because the clause converts the Annex-1 investor's optimization problem for Type-I and -II projects to

$$\max_{T \geq 0} e^{-rT}[V(T) - e^{-r(G-T)}V(G)] = e^{-rT}V(T) - e^{-rG}V(G),$$

with solution T^*.

Part (c) follows because $T^c < G$ for all Type-I and -II projects, implying (as discussed following Proposition 1) that the host-country government would without the CDM sell off such projects immediately at graduation, yielding the host-country citizens profits worth $V(G)$. This is exactly what the citizens receive with the CDM and the clause in place, once the virtual option is exercised at G.

Part (d) follows because the virtual-option clause will dissuade competitive Annex-1 investors from bidding on any Type-III project that the host-country government might try to auction off at some time $T < G$, for the same reason that a monopsonist Annex-1 investor will no longer undertake any such project.

Lastly, part (e) follows because, with the CDM and the clause in place, the host-country citizens again at graduation receive $V(G)$. More specifically, in the competitive case with the virtual option in place, the host-country government will at any time $T < G$ find Annex-1 investors willing to pay only $V(T) - e^{-r(G-T)}V(G)$ up front, because of their commitment to pay $V(G)$ the time of graduation. This reduces the present value of the project from the host-country government's point of view to $V(T) - e^{-r(G-T)}V(G) + e^{-(r+\delta)(G-T)}V(G)$ (since it underestimates or overdiscounts the future virtual-option payment). It can be shown that, as a result, the host-country government will auction off Type-I projects at time $T^* = 0$, and Type-II projects at some time T before T^* (and if $T^c > 0$, after T^c). In the latter case, however, whenever this time lies before T^ℓ, the clause will dissuade competitive Annex-1 investors from bidding until at least time T^ℓ, i.e., until the current value $V(T)$ of the project at least equals the discounted value $e^{-r(G-T)}V(G)$ of the future liability that the winning Annex-1 investor incurs through the clause. □

5.4. *An alternative virtual-option solution*

Although the above, "European" form of the virtual-option clause—European in that the clause has a fixed exercise time G—prevents the low-hanging fruit problem from arising, it has two drawbacks from the host-country citizens' point of view. First, although in the monopsony case the clause ensures that the Annex-1 investor cannot negotiate the host-country government down to below what ought to be its reservation price, $e^{-r(G-T^*)}V(G)$, the clause fails to prevent the Annex-1 investor from extracting all the gains from trade, equal to $V(T^*) - e^{-r(G-T^*)}V(G)$. Second, although in the competitive case the clause ensures that the host-country government will not auction off the project at a time when the competitive price $V(T)$ would dip below $e^{-r(G-T)}V(G)$, the clause fails to ensure that the project is auctioned off at the socially optimal time T^*, thereby dissipating gains from trade of up to $V(T^*) - e^{-r(G-T^*)}V(G)$.

An alternative contractual solution that retains the benefits of the European virtual-option clause but avoids these two drawbacks is the following "American" version of the virtual-option clause—American in that the clause can be exercised at any time up to G:

> The host-country government retains the right to, at any time S up to the time of graduation, undertake this project 'virtually,' by replicating, through monetary transactions between the Annex-1 investor and the host-country government, the revenues and costs that would have accrued to the host-country government had it *physically* undertaken the project itself at time S. This right may be transferred to a third party, or may be bought out by the Annex-1 investor in the absence of any higher third-party bids.

A crucial component of the American virtual-option clause is the provision that the host-country government can, if it chooses to, unbundle the right conferred by the clause from the contract and transfer it to a third party. As we show in the appendix, without the transferability provision the American virtual-option clause will in the competitive case be completely useless, and in the monopsony case effectively convert the monopsony low-hanging fruit problem to the possibly worse competitive low-hanging fruit problem.

If, however, the rights conferred by the American virtual-option clause *are* transferable to a third party, then this radically changes the market situation faced by the host-country government, and as a result also the effectiveness of the clause. The reason is that, because exercising the virtual option is a purely financial transaction, the host-country government should be able to interest *financial* investors in Annex-I countries in buying the option. It seems reasonable to assume that (i) such Annex-1 financial investors will apply the same discount rate as what we might call Annex-1 *physical* investors engaged in the actual, physical undertaking of CDM projects, and (ii) both will have access to the same information about likely future conditions that might affect the value of the option. It also seems reasonable to assume that, again because the virtual option is a purely financial asset, sufficiently many Annex-1 financial investors will be interested in buying it for the option market to be competitive.

If these assumptions hold, then we have the following result:

Proposition 4. *With the transferability provision, the American virtual-option clause will in both the monopsony and competitive case ensure that*

(a) *only Type-I and -II projects are undertaken under the CDM,*

(b) *at the optimal time,*

(c) *without any low-hanging fruit problem arising, and*

(d) *with full rent extraction by the host-country citizens.*

Proof: Parts (a) and (b) follow because the very fact that the host-country government can *potentially* auction off the option to Annex-1 financial investors will guarantee that no Annex-1 physical investor, whether monopsonistic or competitive, will agree to undertake a project at any time T before T^*. The reason is that it will anticipate Annex-1 financial investors bidding up to $e^{-r(T^*-T)}V(T^*)$ for the virtual option, which exceeds the maximum value $V(T)$ that the Annex-1 physical investor could obtain at any $T < T^*$. Since it is never in the host-country government's interest to delay the project beyond T^*, the project will in equilibrium be undertaken exactly at T^*. Because this reasoning applies to any project that the host-country government might contemplate selling off, no Type-III projects will be undertaken under the CDM.

Parts (c) and (d) follow from the fact that if a project is undertaken exactly at T^*, the host-country government's perceived present value $e^{-(r+\delta)(T-T^*)}V(T)$ of auctioning of the virtual option at $T \geq T^*$ is maximized at T^* as well, as is the present value $e^{-r(T-T^*)}V(T)$ to Annex-1 financial investors of exercising the option. That is, the host-country government will immediately auction off the virtual option, and whoever buys the option will immediately exercise it. This in turn implies that the price of the option, which the host-country citizens ultimately receive, will be bid up to the project's full profits $V(T^*)$. This price necessarily exceeds the profits $V(G)$ that the citizens would have received without the CDM. As a result, host country citizens will be better off with the CDM than without it. □

5.5. *Some implementation issues*

Nothing in the virtual option clause prevents the Annex-1 physical investor from bidding on the virtual option as well; in fact, nothing prevents this investor from being given first rights to acquiring the option in the absence of any bids exceeding its own. It is crucial, however, that the host-country government should not be able to *precommit* to transferring the rights to the Annex-1 physical investor, as this would in effect nullify the clause and again result in premature investment at time T^c. This is why the transferability provision requires the host-country government to invite third-party bids on the option. Given this requirement, Annex-1 physical investors will anticipate that, were they to undertake the project at any time $T < T^*$ hoping to buy out the option at a price $V(T)$, they will be outbid by third-party financial investors offering up to $e^{-r(T^*-T)V(T^*)}$.

In equilibrium, then, no project will be undertaken before T^*, and no third-party investor will outbid the Annex-1 investor physically undertaking the project, since both will offer at most $V(T^*)$. The host-country government can therefore immediately transfer the rights conferred by the option clause to the Annex-1 physical investor in return for an overall payment of $V(T^*)$. It follows that *in equilibrium* the virtual-option clause will in fact never be exercised. As a result, no outside verification will ever be needed of the payment that the option commits the owner to make to the Annex-1 physical investor or the stream of credits that the option commits the Annex-1 physical investor to transfer in return. However, the equilibrium can only be sustained if such verification is in principle available when deviations from equilibrium behavior occur. In particular, verification will be needed if, after the project is undertaken at some time T, the host-country government mistakenly auctions off the option at some time $S > T$, or third-party investors mistakenly outbid the Annex-1 physical investor and then mistakenly exercise the option at some time $S > T$.

In such cases, providing a reasonable estimate of what a project would have cost at S had it not been undertaken at T, and what stream of credits the project would have generated from S onwards is likely to be more problematic, the more time has lapsed since T.

One way to minimize potential problems with verification is to limit the time up to which the option can be exercised. Rather than allowing exercise of the option at any time $S \in (T, G]$, the clause could restrict such exercise to a window $S \in (T, T+\Delta]$, for some discrete but small value of Δ. To see why this would not alter the effectiveness of the option, note that were the project undertaken at any time $T < T^*$, the option's value $e^{-r(S-T)}V(S)$ would be strictly increasing in S up to T^*, and the option would therefore be exercised at time $S^*(T) = \min\{T+\Delta, T^*\}$. By single-peakedness of the $e^{-rT}V(T)$ function, an Annex-1 physical investor investing at $T < T^*$ would therefore still incur a liability $e^{-r(S^*(T)-T)}V(S^*(T))$ exceeding the value $V(T)$ of the project's profits, and the clause would therefore still have the desired effect of dissuading such investment.

6. Extensions

In this section, we briefly consider the implications for our results if we relax (one at a time) five simplifying assumptions made in Section 5, namely the assumptions that (i) abatement projects are infinitely lived; (ii) the rate of credit generation $q(T)$ is constant once the project has been undertaken at time T; (iii) host-country governments cannot undertake CDM projects unilaterally before graduation; (iv) host-country citizens have the same discount rate as Annex-1 investors; and (v) host-country governments pass on all profits from CDM projects to their citizens. Proofs of all results discussed in this section are available from the authors upon request.

6.1. *Finite project lifetime*

Although the model of Section 5 assumes that abatement projects are infinitely lived, real-world projects have finite lifetimes, after which they must be renewed. A power plant, for example, might have a lifetime of about 40–50 years until a replacement plant must be constructed. We now explore how this real-world complication affects the results of our model.

Allowing for finite project lifetimes turns out to have few implications for the analysis of *socially optimal* investment in CDM projects. We merely need to redefine $V(T)$ as the current value of a "metaproject" comprised of a single, initial project together with all subsequent renewals of that project. For expositional simplicity, let in this subsection the term "project" refer to a metaproject, i.e., to an initial, finitely lived project and all its subsequent renewals combined, and let "subproject" refer to each individual component project of a metaproject. Also, assume that all subprojects have a fixed finite lifetime of length L, with the project consisting of an infinite sequence of such subprojects. We can then write the value $v(T)$ of subproject started at time T as

$$\begin{aligned} v(T) &= \int_0^L e^{-rt} p(0)q(T)e^{\alpha(T+t)}\,dt - I(T) \\ &= \left[1 - e^{-(r-\alpha)L}\right] \frac{p(0)q(T)e^{\alpha T}}{r-\alpha} - I(T) \end{aligned} \tag{8}$$

and the value $V(T)$ of a project started at time T as

$$V(T) = \sum_{n=0}^{\infty} e^{-rnL} v(T + nL).$$

In the case of the benchmark model, with q and I constant over time, $V(T)$ reduces to

$$V(T) = \frac{p(0)q}{r-\alpha} e^{\alpha T} - \tilde{I}, \tag{9}$$

where

$$\tilde{I} \equiv \sum_{n=0}^{\infty} e^{-rnL} I = \frac{I}{1 - e^{-rL}} \tag{10}$$

is the present value of the project's infinite series of investment costs at intervals of length L. Note that except for replacing I by $\tilde{I}$, expression (9) is identical to expression (1) for the benchmark model with L infinite. For tractability, we limit attention to the benchmark model in this subsection.

If we now assume in addition that (i) the host-country government underestimates or overdiscounts delayed subprojects in the usual manner, i.e., values a subproject delayed until time $T + t$ at $e^{-(r+\delta)t} v(T + t)$ instead of $e^{-rt} v(T + t)$, and that (ii) CDM contracts cover entire projects, then the entire analysis of Section 5 goes through qualitatively unchanged. The only substantive difference is that we can no longer write the host-country government's objective function at time 0 as $e^{-(r+\delta)T} V(T)$. Instead, its objective function becomes

$$\begin{aligned} e^{-(r+\delta)T} \widehat{V}(T) &\equiv e^{-(r+\delta)T} \sum_{n=0}^{\infty} e^{-(r+\delta)nL} v(T + nL) \\ &= e^{-(r+\delta)T} \left\{ \frac{\left[1 - e^{-(r-\alpha)L}\right]}{\left[1 - e^{-(r+\delta-\alpha)L}\right]} \frac{p(0)qe^{\alpha T}}{r-\alpha} - \frac{I}{1 - e^{-(r+\delta)L}} \right\}. \end{aligned}$$

It can be shown that $\widehat{V}(T) < V(T)$ whenever $\widehat{V}(T)$ is positive, implying that a host-country government will undervalue even a project that is undertaken immediately (because it undervalues all successor subprojects to the initial one). Importantly, it can also be shown that the functions $e^{-rT}V(T)$ and $e^{-(r+\delta)T}\widehat{V}(T)$ are single-peaked, and that if we redefine T^* and T^c as the times at which these functions reach their respective maxima, then $T^c < T^*$ for Type-II and -III projects. Recall that the latter inequality drove many of the results of Section 5.

That said, assumption (ii) above is obviously unrealistic: in practice, CDM contracts are likely to cover just a single subproject at a time (or at most a short series of subprojects if the original contract contains renewal provisions). If in fact CDM contracts cover just a single subproject at a time, a number of our results change. First, unlike in the case of infinitely lived projects, a monopsonist Annex-1 investor no longer necessarily undertakes Type-II and -III projects too soon; depending on parameter values, the Annex-1 investor may also undertake such projects at the socially optimal time or too late. Second, in the monopsony case the low-hanging fruit problem does not arise for all subprojects undertaken under the CDM; it arises only for subprojects that straddle the graduation time G, i.e., that do not end exactly at G. Third, in the competitive case the low-hanging fruit problem will arise only if the *first* subproject straddles the graduation time, i.e., if L is such that $T^c + L > G$. In contrast therefore to the monopsony case, where a low-hanging fruit problem can arise for subprojects of arbitrary lifetime L, a low-hanging fruit problem can arise in the competitive case only for subprojects that are "long term" in the sense that L exceeds $G - T^c$.

Importantly, Propositions 3 and 4, which describe the results of mandating respectively the European and American virtual-option clauses, go through unchanged when L is finite, except that the wording of the clauses must be slightly modified. The European form of the clause, for example, becomes

> If the time $T + L$ at which the current subproject ends extends beyond the time of graduation, the host-country government retains the right to undertake all successor subprojects 'virtually' starting from the time of graduation, by replicating the revenue and cost streams that would have accrued to the host-country government had it *physically* undertaken all successor subprojects from G rather than from $T + L$.

and the American form must be modified analogously.

For the remainder of this section, where we consider the implications of relaxing assumptions (ii)–(v) listed above, we revert to the simpler case of infinitely-lived projects.

6.2. *Declining rate of credit generation*

The model of Section 5 assumes that the flow of credits earned by a project is constant over time, equal to $q(T)$ per period, once the project has been undertaken at time T. This assumption is reasonable when considering energy-based carbon abatement projects. A project, for example, that involves converting a power plant to a less carbon-intensive fuel source would indeed yield an essentially constant stream of carbon credits. The assumption is *not* reasonable, however, when considering an important alternative class of CDM projects, namely those that involve planting forests to sequester carbon.[20] Trees sequester carbon at high rates when they are young, but this rate tends to decline over time, and eventually, when the trees reach maturity, drops to zero. A more reasonable specification would therefore have the rate of credit generation for a sequestration project fall over time from T onwards.

Qualitatively, this alternative specification does not affect our analysis of the low-hanging fruit problem and the virtual-option solution to that problem. Although the expression for the current value $V(T)$ of undertaking a sequestration project at time T is different from that given in equation (1), the analysis following that equation goes through unchanged. Quantitatively, however, the assumption of a declining rate of credit generation does have important implications. In particular, as shown by van 't Veld and Plantinga (forthcoming) in a context separate from the CDM, it implies that the socially optimal time to undertake a sequestration project will depend on the rate α at which credit prices are expected to increase. Specifically, the more rapidly the price of carbon credits is expected to increase over time, the more valuable it becomes to delay conversion of land to forest (since delaying conversion implies that the forest will be younger, and hence sequestering carbon at higher rates, at times when those credits are of higher value). The range of sequestration projects that should optimally be undertaken *immediately*, i.e., should *not* be delayed, therefore shrinks with increases in α.[21]

[20]At the COP7 climate negotiations at Marrakech in 2001, where implementation details of the 1997 Kyoto Protocol were worked out, the amount of credits that Annex-1 countries can earn from CDM sequestration (as opposed to abatement) projects was capped at 1% of their base year (1990) emissions. Jotzo and Michaelowa (2002) estimate that as a result, net emissions reductions from CDM sequestration projects will amount to only 67 Mt CO_2/year, compared to 372 Mt $CO_2$2/year from CDM abatement projects. However, as pointed out recently by the World Bank's senior manager for carbon finance, sequestration projects "may in the end be the only significant option for many poor nations with only small industrial sectors and energy use, to benefit from the Clean Development Mechanism (CDM)." (Newcombe, n.d.)

[21]Van 't Veld and Plantinga show that this result holds even if forests are periodically harvested and replanted, rather than left to stand permanently.

In terms of our model, this implies that at higher values of α, a larger range of CDM sequestration projects are likely be of Type II or Type III, and hence potentially the source of a low-hanging fruit problem even in the competitive case.

6.3. *Unilateral CDM projects*

Our analysis above assumed implicitly that either legal or practical constraints will prevent developing countries from undertaking CDM projects "unilaterally," i.e., from using their own funds to finance the projects and then selling any credits generated to Annex-1 countries. In reality, it seems increasingly likely that unilateral CDM will in fact be permitted under the rules of the Kyoto Protocol,[22] and at least one commentator (Rajamani, 1999) has characterized unilateral CDM as a solution to the low-hanging fruit problem, arguing that "this may well be an ingenious way for developing countries to gather the 'low hanging fruit' themselves."

Of course, even if legal constraints are removed, practical constraints such as lack of capital or technical expertise may still deter developing countries from in fact investing in unilateral CDM projects.[23] On the other hand, it is plausible that such practical constraints will for at least some developing countries be relaxed before the time of their graduation.

One way in which unilateral CDM would affect our analysis is that the distinction between overdiscounting and underestimation becomes potentially relevant. Whereas in the competitive case an underestimating host-country government will always be indifferent about either auctioning off a project at time T or undertaking the project unilaterally—perceiving the current value of either course of action to be $V(T)$—an overdiscounting host-country government will always strictly prefer auctioning off a project. The reason is that it will perceive the current value of undertaking a project unilaterally at T to be

$$V^u(T) \equiv \int_0^\infty e^{-(r+\delta)t} p(0) e^{\alpha(T+t)} q(T,t)\, dt - I(T), \tag{11}$$

[22]Although at the COP7 climate negotiations it was agreed in principle that unilateral CDM projects would be allowed, this agreement was not explicitly reflected in the text of the Marrakech Accords. Moreover, according to Wilder, Willis and Carmody (2004) "at COP9 in Milan [in 2003] some CDM Executive Board members questioned the concept of Unilateral CDM Projects." More recently, at a meeting in September 2004, the Executive Board removed an important technical block for such projects, by allowing non-Annex-1 countries and firms to officially transfer credits to Annex-1 countries. (PointCarbon, 2004).

[23]China, for example, has stated that unilateral CDM projects are not one of its priorities, as such projects involve no technology transfer and no up-front investment from Annex-1 investors—investment that is needed to help overcome capital constraints in the Chinese economy (Tangen and Heggelund, 2003).

where $q(T,t)$ is constant after T for abatement projects, and declining in $t-T$ for sequestration projects. Because the host-country government discounts revenues from credits earned in future at rate $r+\delta$, whereas Annex-1 investors discount those same revenues at rate r, the value $V^u(T)$ that the host-country government places on undertaking a project unilaterally at time T and then earning those receipts gradually over time is always less than the value $V(T)$ that Annex-1 investors are willing to bid up-front at time T.

If we let T^u denote the optimal time at which an overdiscounting host-country government would undertake a project unilaterally, i.e.,

$$T^u \equiv \arg\max_{T\geq 0} e^{-(r+\delta)T} V^u(T),$$

we find that in the benchmark model $T^u > T^*$ for abatement projects, while in a simple extension of the benchmark model that has the rate of credit generation decline exponentially with $T-t$ for sequestration projects, $T^u \gtreqless T^*$.[24]

None of this matters in practice to the low-hanging fruit problem in the competive case. In this case, an overdiscounting host-country government will strictly prefer to auction off a project at time T^c to undertaking it unilaterally at time T^u, while an underestimating host-country government will be indifferent about doing either at T^c. Either way, for either type of host-country government, a low-hanging fruit problem will arise whenever $T^c < T^\ell$.

In the monopsony case, however, the host-country government's ability to undertake projects unilaterally may raise its reservation price, thereby mitigating the low-hanging fruit problem. For an underestimating host-country government, the reservation price will in fact increase to the point of full rent extraction, which may or may not eliminate the low-hanging fruit problem. To see this, recall that an underestimating host-country government will be willing to undertake the project unilaterally at T^c, and so its reservation price for allowing the Annex-1 investor to undertake the project at any time $T < T^c$ will be $e^{-(r+\delta)(T^c-T)}V(T^c)$. This leaves the Annex-1 investor with

[24]The reason why paradoxically an overdiscounting, "impatient" host-country government would unilaterally undertake abatement projects *later* than optimal is that it overvalues the marginal benefit of delay for such projects, namely the value of postponing the initial investment cost (the host-country government perceives that marginal benefit to equal $(r+\delta)I$ rather than rI). The reason why the same host-country government might undertake sequestration projects *sooner* than is optimal is that, as briefly noted above, such projects feature an additional marginal benefit of delay, namely the value of having trees be younger in future and thereby sequestering higher-valued carbon at higher rates. The overdiscounting host-country government will overdiscount, and thereby *under*value, this second marginal benefit of delay, which for low enough values of δ tends to outweigh its overvaluing of the first marginal benefit.

rents $e^{-rT}\left[V(T)-e^{-(r+\delta)(T^c-T)}V(T^c)\right] = e^{\delta T}\left[e^{-(r+\delta)}V(T)-e^{-(r+\delta)T^c}V(T^c)\right]$. But the second expression in brackets is by definition negative for any $T \neq T^c$. It follows that the Annex-1 investor can do no better than offering to undertake the project at T^c, at zero profit. If, then, it happens to be the case that $T^c \geq T^\ell$, no low-hanging fruit problem will arise; if, however, $T^c < T^\ell$, then the low-hanging fruit problem is merely mitigated.

For an overdiscounting host-country government, the low-hanging fruit problem is mitigated whenever the host-country government's perceived value $V^u(T^u)$ from undertaking the project unilaterally at T^u exceeds its perceived value $e^{-(r+\delta)(G-T^u)}V(G)$ from waiting until G and then auctioning off the project. In such cases, the Annex-1 investor's rents from undertaking the project at any time $T < T^u$ become $e^{-rT}\left[V(T)-e^{-(r+\delta)(T^u-T)}V^u(T^u)\right]$, and it can be shown that these rents are in the benchmark model (extended for sequestration projects in the manner described above) always maximized at some $T^m < T^u$. However, a mitigated low-hanging fruit problem will still exist if the host-country government's reservation price $e^{-(r+\delta)(T^u-T^m)}V^u(T^u)$ at T^m falls short of the discounted value $e^{-r(G-T^m)}V(G)$ that host-country citizens would have obtained without the CDM. It can be shown that at reasonable parameter values the latter condition may indeed hold, for both carbon abatement and sequestration projects.

In sum, allowing unilateral CDM projects provides only a partial solution to the low-hanging fruit problem: while it sometimes mitigates the problem, it fails to always eliminate it.

It turns out, moreover, that this partial solution mixes badly with the full solution to the low-hanging fruit problem proposed in this paper. In particular, if either of the virtual-option clauses were implemented, host-country citizens would be weakly *worse* off if in addition unilateral CDM projects were allowed; doing so would make the virtual-option clauses no longer binding in some cases where they would otherwise prevent a low-hanging fruit problem.

This is easiest to see in the competitive case, or in the monopsony case for an underestimating host-country government. As discussed above, in these cases the host-country government will either undertake the project itself or contract the project out at T^c, and a low-hanging fruit problem will therefore exist if $T^c < T^\ell$. Neither the European nor the American virtual-option clause will be able to prevent this low-hanging fruit problem, however: although Annex-1 investors will refuse to undertake the project in the presence of either clause (until respectively T^ℓ and T^*) this will merely induce the host-country government to undertake the project unilaterally at T^c, leaving the same low-hanging fruit problem in place. In the monopsony case for an overdiscounting host-country government, the virtual-option clauses become similarly non-binding whenever $T^u < T^\ell$, as may be true for carbon sequestration projects.

6.4. *Higher host-country citizen discount rate*

An important caveat to the results presented thus far is that the virtual-option clauses are guaranteed to increase the returns from CDM projects to host-country citizens only if the host-country citizens' discount rate coincides with that of Annex-1 investors. It is plausible, however, that the discount rate of host-country citizens in some developing countries may be higher. Standard analysis of the social discount rate (see, e.g., Arrow et al., 1996) shows that, all else equal, this rate increases in the anticipated rate of consumption growth. It follows that in developing countries that expect to grow at higher rates than Annex-1 countries, the discount rate of host-country citizens may well exceed that of Annex-1 investors.

If this is indeed the case, inclusion of either the European or the American virtual-option clause will still prevent the low-hanging fruit problem from arising, but may nevertheless make host-country citizens worse off than they would be without the clause. To see this, let $\tilde{r}$ denote the host-country citizens' discount rate, where $\tilde{r} > r$, and assume that $\delta = 0$, so the host-country government neither underestimates the value of delaying CDM projects, nor overdiscounts that value relative to the discount rate applied by its citizens. Assume also that the host-country government does not face Annex-1 investors with monopsony power, i.e., that we are in the perfectly competive case.

Without the virtual-option clauses in place, the host-country government would under these assumptions auction off CDM projects strictly before T^*, at time

$$\widetilde{T}^c \equiv \arg\max_{T\geq 0} e^{-\tilde{r}T} V(T),$$

and host-country citizens would receive $V(\widetilde{T}^c)$ at that time. No low-hanging fruit problem would arise, because by revealed preference $V(\widetilde{T}^c)$ weakly exceeds the discounted value $e^{-\tilde{r}(G-\widetilde{T}^c)}V(G)$ of the host-country citizens' receipts in the absence of the CDM, and strictly so if $\widetilde{T}^c < G$.

With the European virtual-option clause in place, however, and if $\widetilde{T}^c < T^\ell$, the host-country citizens' receipts would just equal those in the absence of the CDM. The reason is that the host-country government would find no bidders for the project until T^ℓ and even then receive nothing until time G, when the option clause would be exercised at price $V(G)$. If, on the other hand, $\widetilde{T}^c \geq T^\ell$, the host-country citizens would receive $V(\widetilde{T}^c) - e^{-r(G-\widetilde{T}^c)}V(G)$ at $\widetilde{T}^c$ (the value of the project less the discounted value of the option clause from the Annex-1 investor's point of view), and $V(G)$ at time G. Discounted to time $\widetilde{T}^c$, their total receipts would be worth $V(\widetilde{T}^c) - e^{-r(G-\widetilde{T}^c)}V(G) + e^{-\tilde{r}(G-\widetilde{T}^c)}V(G)$. This is below their receipts of $V(\widetilde{T}^c)$ without the clause, though above their receipts of $e^{-\tilde{r}(G-\widetilde{T}^c)}V(G)$ without the CDM.

With the American virtual-option clause in place, and if $T^* < G$, the host-country citizens would receive $V(T^*)$ at time T^*, or $e^{-\tilde{r}(T^*-\widetilde{T}^c)}V(T^*)$ when discounted to time $\widetilde{T}^c$. This is again less than $V(\widetilde{T}^c)$, though more than $e^{-\tilde{r}(G-\widetilde{T}^c)}V(G)$.

Intuitively, the two clauses prevent the low-hanging fruit problem by precommiting the host-country government to accepting no less than what competitive Annex-1 investors would pay for the option to undertake a CDM project at either time G, for the European clause, or time T^*, for the American clause. However, the clauses also precommit the host-country government to accecpting those payments *no sooner than* times G and T^*, respectively. The latter feature of the clauses will make host-country citizens with high discount rates unambiguously worse off than they would be without the clauses *if* there are no CDM-market imperfections, whether from Annex-1 investor monopsony power or from underestimation or overdiscounting by the host-country government. More generally, if market imperfections do exist, host-country citizens with high discount rates will need to weigh the benefits of the virtual-option clauses in terms of mitigating the consequences of these imperfections against their costs in terms of of postponing some gains from some CDM projects.

6.5. *Rent-dissipating corruption*

A final complication of the model worth considering is that corruption by host-country governments may realistically result in not just suboptimal decisions with respect to the pricing and timing of CDM projects, but also suboptimal use, from the host-country citizens' point of view, of the profits from those projects. Although our analysis above assumed that the host-country government passes on all profits to its citizens, the unfortunate reality in some developing countries is that a share of those profits may in fact be diverted by corrupt officials for their private use, and hence not reach host-country citizens at all.

The virtual-option clauses proposed in this paper do nothing to prevent such "outright" corruption. In fact, by increasing CDM profits, the clauses if anything increase the scope for profit diversion. It is worth noting, however, that if such corruption is anticipated to decline over time as the host country's governance structure matures, then the fact that the clauses tend to postpone the actual transfer of CDM profits to the host-country government, which we noted in the previous subsection is a negative effect for developing countries with high growth prospects, may be viewed as a positive effect for developing countries with high current levels of corruption. Moreover, this may be a reason for preferring the European form of the clause over the American form, as the former tends to postpone CDM profit transfers to a greater extent.

7. Conclusions

Our analysis of the low-hanging fruit problem suggests that, given political and institutional realities in developing countries, there is a real risk that the stock of cheap CO_2-abatement projects in these countries will be exploited too soon, at prices that do not fully compensate for the indirect opportunity cost of undertaking the projects under the CDM. However, this indirect opportunity cost is not that described in the standard characterization of the low-hanging fruit problem, which ignores the future presence of a market for carbon credits. Rather, the opportunity cost simply equals the value of an option to delay undertaking the projects until after a developing country graduates, i.e., takes on emissions-reduction commitments of its own. Recognizing this fact leads to the simple solution for the low-hanging fruit problem laid out in this paper, involving the use of a "virtual" option clause in CDM investment contracts.

Appendix

Proposition 5. *Without the transferability provision, the American virtual-option clause will*

(a) *in the competitive case be completely useless,*

(b) *in the monopsony case effectively convert the monopsony low-hanging fruit problem to the possibly worse competitive low-hanging fruit problem.*

Proof: Part (a) follows because in the competitive case the host-country government will perceive the optimal time to exercise the option, conditional on having auctioned off the project at any time $T < G$, to be

$$S^* = \max_{S \in [T,G]} e^{-(r+\delta)(S-T)} V(S).$$

If $T < T^c$, then $S^* = T^c$, and Annex-1 investors will therefore evaluate their liability from the option clause as equal to $e^{-r(T^c - T)} V(T^c)$ in present value. Since this strictly exceeds the value $V(T)$ of undertaking the project at $T < T^c$, no Annex-1 investor will bid on the project. If $T \geq T^c$, however, then $S^* = T$. Annex-1 investors will therefore evaluate their liability from the option clause as equal to $V(T)$, leaving them with zero rents, and thereby leaving them indifferent about undertaking the project at any $T \geq T^c$. As a result, the host-country government will choose to auction off the project exactly at T^c, when its perceived present value $e^{-(r+\delta)T} V(T)$ of exercising the option immediately (while receiving zero rents on the project contract itself) is maximized. In sum, the virtual-option clause results in exactly the same equilibrium as would arise without the clause, with exactly the same potential low-hanging fruit problem.

Part (b) follows because in the monopsony case, by the same reasoning as in the competitive case, the clause will dissuade the monopsonist Annex-1 investor from undertaking any project before T^c, but will leave the Annex-1 investor with zero rents for any project undertaken after T^c. If this is interpreted to imply that the host-country government will effectively be able to choose the time to start the project, then, just as in the competitive case, the host-country government will choose T^c. By Part (c) of Proposition 2, this is guaranteed to eliminate the low-hanging fruit problem for all Type-I projects and for some range of Type-II projects with T^* close to 0. For other projects, however, it merely replaces the monopsony low-hanging fruit problem by the competitive low-hanging fruit problem. In general, either of these could be worse. □

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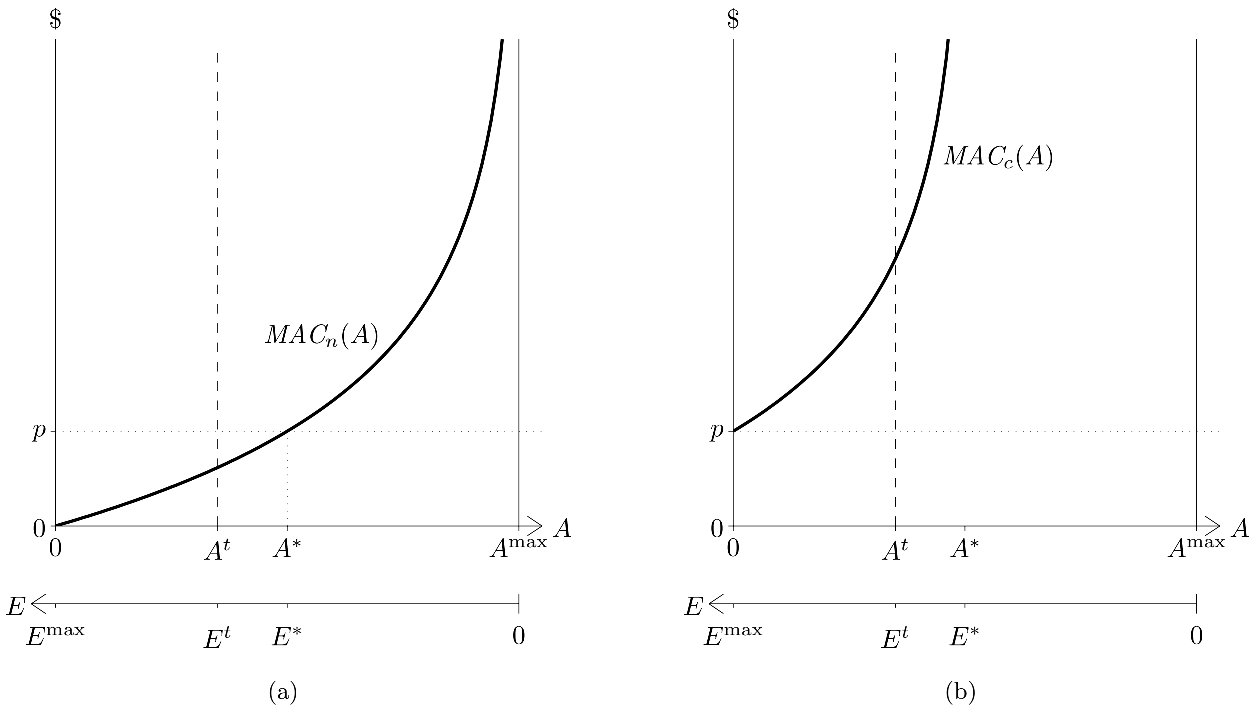

FIGURE 1. Effects of CDM participation on a developing country's marginal abatement costs upon graduation.

Reviewer Appendix to

USING VIRTUAL OPTIONS TO TURN "ECO-COLONIALISM" INTO "CLEAN DEVELOPMENT"

Additional Proofs

To simplify the exposition of some of these proofs, we introduce the following notation. Let

$$a(x) > (<)\, 0 \overset{s}{\Leftrightarrow} b(x) > (<)\, 0$$

denote that $b(x) = f(x)a(x)$ for some strictly positive function $f(x)$, implying that $a(x)$ and $b(x)$ are equivalent in sign. Also, let

$$a(x) > (<)\, 0 \overset{x}{\Leftarrow} b(x) > (<)\, 0$$

denote that (i) $x > 0$, (ii) $\lim_{x\to 0} a(x) = 0$, and (iii) $b(x) = a'(x)$, implying that $b(x) > (<)\, 0$ is sufficient for $a(x) > (<)\, 0$.

It will also be useful to establish the following lemma:

Lemma 1. *For any positive A, B, C, and D, if (i) $A \geq C$, (ii) $C > D$, and (iii) $A/B > C/D$, then $A - B > C - D$.*

Proof: Rewrite (iii) as $B/A < D/C$, which implies

$$\frac{A-B}{A} > \frac{C-D}{C}.$$

Also, (i) and (ii) combined imply

$$\frac{C-D}{C} \geq \frac{C-D}{A}.$$

The result $A - B > C - D$ follows by transitivity. □.

Subsection 6.1: With finite project lifetimes, the host-country government's objective function becomes

$$e^{-(r+\delta)T}\widehat{V}(T) \equiv e^{-(r+\delta)T}\sum_{n=0}^{\infty} e^{-(r+\delta)nL} v(T+nL) \tag{A1}$$

$$= e^{-(r+\delta)T}\left\{ \frac{\left[1-e^{-(r-\alpha)L}\right]}{\left[1-e^{-(r+\delta-\alpha)L}\right]}\frac{p(0)qe^{\alpha T}}{r-\alpha} - \frac{I}{1-e^{-(r+\delta)L}} \right\}. \tag{A2}$$

Proof: The discounted value of single project as perceived by an overdiscounting or underestimating host-country government is

$$e^{-(r+\delta)T}v(T) = e^{-(r+\delta)T}\left\{ \int_0^L e^{-rt}p(0)qe^{\alpha(T+t)}\, dt - I \right\}.$$

$$= e^{-(r+\delta)T}\left\{ \left[1-e^{-(r-\alpha)L}\right]\frac{p(0)qe^{\alpha T}}{r-\alpha} - I \right\}.$$

and that of the n-th successor project is

$$e^{-(r+\delta)(T+nL)}v(T+nL) = e^{-(r+\delta)(T+nL)}\left\{\left[1-e^{-(r-\alpha)L}\right]\frac{p(0)qe^{\alpha(T+nL)}}{r-\alpha} - I\right\}$$
$$= e^{-(r+\delta)T}\left\{e^{-(r+\delta-\alpha)nL}\left[1-e^{-(r-\alpha)L}\right]\frac{p(0)qe^{\alpha T}}{r-\alpha} - e^{-(r+\delta)nL}I\right\}.$$

The result follows by summing over n. □

Subsection 6.1: $\widehat{V}(T) < V(T)$ whenever $\widehat{V}(T)$ is positive.

Proof: Recall first from (9) and (10) that

$$e^{-rT}V(T) = e^{-rT}\left\{\frac{p(0)qe^{\alpha T}}{r-\alpha} - \frac{I}{1-e^{-rL}}\right\}. \tag{A3}$$

Comparison with (A2) above shows that $\lim_{\delta\to 0}\widehat{V}(T) = V(T)$. It follows that

$$\widehat{V}(T) - V(T) < 0$$
$$\overset{\delta}{\Leftarrow} \quad \frac{\partial}{\partial\delta}\widehat{V}(T) < 0. \tag{A4}$$

Substituting from (A2) and letting $\overline{R} \equiv [1-e^{-(r-\alpha)L}]p(0)qe^{\alpha T}/(r-\alpha)$ shows that

$$\widehat{V}(T) = \frac{\overline{R}}{1-e^{-(r+\delta-\alpha)L}} - \frac{Le^{-(r+\delta)L}}{1-e^{-(r+\delta)L}}.$$

Also, differentiating w.r.t. δ yields that (A4) can be rewritten as

$$\underbrace{\frac{\overline{R}}{1-e^{-(r+\delta-\alpha)L}}}_{A_1}\underbrace{\frac{Le^{-(r+\delta-\alpha)L}}{1-e^{-(r+\delta-\alpha)L}}}_{A_2} > \underbrace{\frac{I}{1-e^{-(r+\delta)L}}}_{B_1}\underbrace{\frac{Le^{-(r+\delta)L}}{1-e^{-(r+\delta)L}}}_{B_2}.$$

Since it is easy to show that for any $L > 0$ and $x > 0$,

$$\frac{d}{dx}\left[\frac{Le^{-x}}{1-e^{-x}}\right] < 0,$$

we have that $A_2 > B_2$. It follows that $A_1 > B_1$, or $\widehat{V}(T) = A_1 - B_1 > 0$ is sufficient for (A4). □

Subsection 6.1: The functions $e^{-rT}V(T)$ and $e^{-(r+\delta)T}\widehat{V}(T)$ are single-peaked.

Proof: To show that $e^{-rT}V(T)$ is single-peaked, it is sufficient to show that $\partial^2 e^{-rT}V(T)/\partial T^2 < 0$ whenever $\partial e^{-rT}V(T)/\partial T = 0$.

Differentiating $e^{-rT}V(T)$ w.r.t. T yields

$$\frac{d}{dT}\left[e^{-rT}V(T)\right] = e^{-rT}\left\{-p(0)qe^{\alpha T} + \frac{rI}{1-e^{-rL}}\right\} \tag{A5}$$

and differentiating again,

$$\frac{d^2}{dT^2}\left[e^{-rT}V(T)\right] = -re^{-rT}\left\{-p(0)qe^{\alpha T} + \frac{rI}{1-e^{-rL}}\right\} - \alpha e^{-rT}p(0)qe^{\alpha T}.$$

It follows that

$$\left.\frac{d^2}{dT^2}\left[e^{-rT}V(T)\right]\right|_{\frac{\partial}{\partial T}[e^{-rT}V(T)]=0} = -\alpha e^{-rT}p(0)qe^{\alpha T} < 0.$$

The proof that $e^{-(r+\delta)T}\widehat{V}(T)$ is single peaked is strictly analogous. □

Subsection 6.1: If we redefine T^* and T^c as the times at which the functions $e^{-rT}V(T)$ and $e^{-(r+\delta)T}\widehat{V}(T)$ reach their respective maxima, then $T^c < T^*$ for Type-II and -III projects.

Proof: By single-peakedness of the two functions, it is sufficient to show that $de^{-rT^c}V(T^c)/dT > 0$.

Differentiating (A2) w.r.t. T yields

$$\frac{d}{dT}\left[e^{-(r+\delta)T}\widehat{V}(T)\right] = e^{-(r+\delta)T}\left\{-(r+\delta-\alpha)\frac{1-e^{-(r-\alpha)L}}{1-e^{-(r+\delta-\alpha)L}}\frac{p(0)qe^{\alpha T}}{r-\alpha} + \frac{(r+\delta)I}{1-e^{-(r+\delta)L}}\right\} \tag{A6}$$

At T^c, where this derivative is zero, we therefore have

$$(r+\delta-\alpha)\frac{1-e^{-(r-\alpha)L}}{1-e^{-(r+\delta-\alpha)L}}\frac{p(0)qe^{\alpha T}}{r-\alpha} = \frac{(r+\delta)I}{1-e^{-(r+\delta)L}}. \tag{A7}$$

Substituting this into (A5) yields that

$$\frac{d}{dT}\left[e^{-rT^c}V(T^c)\right] > 0$$

$$\overset{s}{\Leftrightarrow} \quad \frac{\frac{(r+\delta-\alpha)L}{1-e^{-(r+\delta-\alpha)L}}}{\frac{(r+\delta)L}{1-e^{-(r+\delta)L}}} - \frac{\frac{(r-\alpha)L}{1-e^{-(r-\alpha)L}}}{\frac{rL}{1-e^{-rL}}} > 0.$$

Sufficient for the latter inequality is that for any $x > 0$ and $y > 0$,

$$\frac{\partial}{\partial y}\left[\frac{\frac{y}{1-e^{-y}}}{\frac{x+y}{1-e^{-(x+y)}}}\right] > 0,$$

$$\overset{s}{\Leftrightarrow} \quad \frac{e^y-1}{y}\frac{x}{x+y} - \frac{e^{x+y}-e^y}{e^{x+y}-1} > 0,$$

$$\overset{x}{\Leftarrow} \quad \frac{e^y-1}{(x+y)^2} - \frac{(e^y-1)e^{x+y}}{(e^{x+y}-1)^2} > 0,$$

$$\overset{s}{\Leftrightarrow} \quad (e^z-1)^2 - z^2e^z > 0, \qquad \text{where } z \equiv x+y$$

$$\overset{z}{\Leftarrow} \quad 2(e^z-1)e^z - 2ze^z - z^2e^z > 0,$$

$$\overset{s}{\Leftrightarrow} \quad 2e^z - 2 - 2z - z^2 > 0,$$

$$\overset{z}{\Leftarrow} \quad 2e^z - 2 - 2z > 0,$$

$$\overset{s}{\Leftrightarrow} \quad e^z - (1 + z) > 0.$$

□

Subsection 6.1: If CDM contracts cover just a single subproject at a time, Proposition 1 must be modified as follows:

Proposition 6. *If the host-country government faces a monopsonist Annex-1 investor and L is finite,*

(a) *the Annex-1 investor will undertake not just all Type-I and -II projects, but also some Type-III projects, so that the range of projects undertaken under the CDM will be too large;*

(b) *depending on parameter values, the Annex-1 investor may undertake the Type-II and -III projects too soon, at the socially optimal time, or too late;*

(c) *the low-hanging fruit problem will arise for all projects undertaken by the Annex-1 investor under the CDM, unless the $m(T)$-th subproject happens to end exactly at graduation time G.*

Proof: The proof of Part (a) is strictly analogous to that of Part (a) of Proposition 1. Again, the host-country government will auction off any project with $T^c < G$ immediately at G if it is not undertaken earlier under the CDM. As a result, if the Annex-1 investor undertakes the project at some time $T \in [T^c, G)$, we have that

$$e^{-(r+\delta)T}\widehat{V}(T) > e^{-(r+\delta)G}\widehat{V}(G),$$

or, rearranging,

$$\widehat{V}(T) > e^{-(r+\delta)(G-T)}\widehat{V}(G). \tag{A8}$$

Contrary to the case of Section 5, however, where we discussed the analogous inequality $V(T) > e^{-(r+\delta)(G-T)}V(G)$, in the above inequality the right-hand side does not represent the host-country government's reservation price. By our assumption above, the Annex-1 investor can only count on undertaking the first $m(T)$ subprojects of a project, and the host-country government will therefore still get to auction off the remainder, i.e., all subprojects from the $(m(T)+1)$-st onwards, after the $m(T)$-th subproject is finished at time $T + m(T)L \geq G$.

If the subproject lifetime L happens to divide exactly into $G - T$, then even without the CDM, the host-country government's first auction will occur at G. Moreover, the proceeds to host-country citizens from this, and all subsequent auctions will be identical to the proceeds they would have received without the CDM. This is because, by our assumption that I and q are constant over time, the infinite series of subprojects from the 1-st subproject onwards—which would be auctioned off starting at time G without the CDM—is identical to that from the $(m(T)+1)$-st subproject onwards—which is auctioned off starting at time G with the CDM. The auctions of both yield $e^{-r(G-T)}V(G)$ in present value when discounted to time T at rate r, and the host-country government's perceived proceeds from the auctions of both are identical as well, equal to $e^{-(r+\delta)(G-T)}\widehat{V}(G)$.

If the subproject lifetime L does *not* divide exactly into $G - T$, however, the host-country government's first auction under the CDM will be delayed until time $T + m(T)L > G$. As a result, its perceived proceeds fall to $e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L)$, and it will demand a reservation price of $e^{-(r+\delta)(G-T)}\widehat{V}(G) - e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L)$ to make up for the difference.

The Annex-1 investor will earn positive rents from undertaking the first $m(T)$ subprojects as long as its gross profits $V(T) - e^{-rm(T)L}V(T + m(T)L) = \sum_{n=0}^{m(T)-1} e^{-rnL}v(T + nL)$ exceed this reservation price. But because the host-country government undervalues all subprojects except the very first one, we have that

$$V(T) - e^{-rm(T)L}V(T + m(T)L) \geq \widehat{V}(T) - e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L). \qquad \text{(A9)}$$

Moreover, subtracting $e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L)$ from both sides of (A8) yields

$$\widehat{V}(T) - e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L) > e^{-(r+\delta)(G-T)}\widehat{V}(G) - e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L). \qquad \text{(A10)}$$

Combining (A9) and (A10) yields that the Annex-1 investor's rents

$$[V(T) - e^{-rm(T)L}V(T + m(T)L)] - [e^{-(r+\delta)(G-T)}\widehat{V}(G) - e^{-(r+\delta)m(T)L}\widehat{V}(T + m(T)L)]$$

are strictly positive, which completes the proof of Part (a).

Part (b) follows because for all Type-II and -III projects that the Annex-1 investor undertakes, the time at which it will optimally start its series of $m(T)$ subprojects is given by

$$T^m \equiv \arg\max_{T\in[0,G)} e^{-rT}\Big\{\Big[V(T) - e^{-rm(T)L}V(T+m(T)L)\Big]$$
$$- \Big[e^{-(r+\delta)(G-T)}\widehat{V}(G) - e^{-(r+\delta)m(T)L}\widehat{V}(T+m(T)L)\Big]\Big\}. \quad \text{(A11)}$$

Note that at critical times T where L divides exactly into $G-T$, so that $T+m(T)L = G$, the host-country government's reservation price drops to zero: if the Annex-1 investor finishes its last subproject exactly at time G, there is no opportunity cost from participating in the CDM. Note also that at these critical times, $m(T)$ drops discontinuously from $(G-T)/L$ to $(G-T)/L-1$. As a result, the Annex-1 investor's overall rent (the maximand of (A11)) falls discontinuously by the rent $[e^{-rm(T)L} - e^{-(r+\delta)m(T)L}]v(T+m(T)L)$ on the $m(T)$-th subproject that it now no longer gets to undertake.

These discontinuities complicate the solution to the Annex-1 investor's optimal timing problem. For any segment of its rent function corresponding to a fixed value m of $m(T)$, however, the derivative of the Annex-1 investor's rents with respect to T can be written as

$$\frac{d}{dT}\left[e^{-rT}V(T)\right] - \delta e^{\delta T}e^{-(r+\delta)G}\widehat{V}(G)$$
$$- \frac{d}{dT}\left[e^{-rT}\left\{e^{-rmL}V(T+mL) - e^{-(r+\delta)mL}\widehat{V}(T+mL)\right\}\right]. \quad \text{(A12)}$$

This derivative will be zero at T^m if T^m lies in the interior of such a segment, weakly negative if $T^m = 0$, and possibly positive if T^m lies at the upper end of a segment.

Comparing the derivative with the analogous derivative that applies in the case of infinitely lived projects,

$$\frac{d}{dT}\left[e^{-rT}V(T)\right] - \delta e^{\delta T}e^{-(r+\delta)G}V(G). \quad \text{(A13)}$$

we find that, apart from the distortion captured by the second term in (A12)—which is present also in (A13) and induces the Annex-1 investor to undertake Type-II and -III projects too soon—there is now an additional distortion, captured by the third term in (A12). This additional distortion arises because the Annex-1 investor does not internalize the full opportunity cost to the host country of having the $(m+1)$-st subproject be postponed until after G: it internalizes only the part of this cost captured in the host-country government's reservation price.

Taken alone, the second distortion induces the Annex-1 investor to start projects too late, because the third term in (A12) is negative for all $T \geq T^*$. To see this, rewrite

$$\frac{d}{dT}\left[e^{-rT}\left\{e^{-rmL}V(T+mL) - e^{-(r+\delta)mL}\widehat{V}(T+mL)\right\}\right] < 0$$

as

$$e^{\delta mL}\frac{d}{dT}\left[e^{-r(T+mL)}V(T+mL)\right] < \frac{d}{dT}\left[e^{-r(T+mL)}\widehat{V}(T+mL)\right]. \tag{A14}$$

Since $d/dT[e^{-r(T+mL)}V(T+mL)] \leq 0$ for all $T \geq T^*$, we also have

$$e^{\delta mL}\frac{d}{dT}\left[e^{-r(T+mL)}V(T+mL)\right] \leq \frac{d}{dT}\left[e^{-r(T+mL)}V(T+mL)\right].$$

It follows that

$$\frac{d}{dT}\left[e^{-r(T+mL)}V(T+mL)\right] < \frac{d}{dT}\left[e^{-r(T+mL)}\widehat{V}(T+mL)\right]$$

or equivalently

$$\frac{d}{dT}\left[e^{-rT}\left\{V(T) - \widehat{V}(T)\right\}\right] < 0 \tag{A15}$$

is sufficient for (A14). After substituting from (A5) and (A6), taking the derivative, and letting $\overline{R} \equiv [1 - e^{-(r-\alpha)L}]p(0)qe^{\alpha T}/(r-\alpha)$, this inequality reduces to the equivalent inequality

$$\underbrace{\frac{\overline{R}}{1-e^{-(r-\alpha)L}}}_{A} - \underbrace{\frac{\overline{R}}{1-e^{-(r+\delta-\alpha)L}}}_{B} > \underbrace{\frac{rI}{1-e^{-rL}}}_{C} - \underbrace{\frac{rI}{1-e^{-(r+\delta)L}}}_{D}.$$

By Lemma 1, this inequality will hold if (i) $A \geq C$, (ii) $C > D$, and (iii) $A/B > C/D$.

That (i) $A \geq C$ follows from

$$\frac{d}{dT}\left[e^{-rT^*}V(T^*)\right] = e^{-rT^*}\left[-p(0)qe^{\alpha T^*} + \frac{rI}{1-e^{-rL}}\right] = 0,$$

which implies that $A \geq C$ for all $T \geq T^*$. That (ii) $C > D$ is immediate by inspection. Finally, to show that (iii) $A/B > C/D$, it is sufficient to show that for any $L > 0$, $r > 0$ and $\delta > 0$,

$$\frac{d}{dr}\left[\frac{1-e^{-(r+\delta)L}}{1-e^{-rL}}\right] < 0,$$

$$\overset{s}{\Leftrightarrow} \quad e^{-(r+\delta)L} - e^{-rL} < 0.$$

It can be shown also (by example) that at reasonable parameter values either of the distortions captured by the latter two terms in eqn:Tmfocf may dominate, or they may just offset each other.

The Annex-1 investor may therefore start Type-II and -III projects either too soon, at the socially optimal time, or too late.

Part (c) follows because the host-country government's undervalues any delay-induced reduction in proceeds that represents the opportunity cost to host-country citizens of participating in the CDM (defined, as usual, as the cost over and above the investment costs I of each subproject undertaken by the Annex-1 investor). Mathematically,

$$e^{-r(G-T)}V(G) - e^{-rmL}V(T+mL) > e^{-(r+\delta)(G-T)}\widehat{V}(G) - e^{-(r+\delta)mL}\widehat{V}(T+mL), \tag{A16}$$

where the left-hand side represents the host-country citizens' valuation of this reduction when discounted at rate r to the time T at which the Annex-1 investor undertakes the project, and the right-hand side represents the host-country government's valuation when discounted at rate $r+\delta$ to that same time.

Rather than showing that (A16) holds at $T = T^m < G$ and $mL = m(T^m)L > G - T^m$, it is easier to show that it holds more generally for all T such that $T \in [T^c, G)$ and all mL such that $mL > G - T$.

First, let $\widehat{T} \equiv T + (m-1)L$, and $x \equiv G - \widehat{T}$. Substituting this into (A16) and simplifying yields

$$e^{-rx}V(\widehat{T}+x) - e^{-rL}V(T+mL) > e^{-\delta(m-1)L}\left[e^{-(r+\delta)x}\widehat{V}(\widehat{T}+x) - e^{-(r+\delta)L}\widehat{V}(\widehat{T}+L)\right]$$

A sufficient condition for this to hold is that

$$e^{-rx}V(\widehat{T}+x) - e^{-rL}V(T+mL) > e^{-(r+\delta)x}\widehat{V}(\widehat{T}+x) - e^{-(r+\delta)L}\widehat{V}(\widehat{T}+L).$$

After substituting from (A3) and (A2), and letting $\overline{R} \equiv [1 - e^{-(r-\alpha)L}]p(0)qe^{\alpha\widehat{T}}/(r-\alpha)$, this inequality can be rewritten as

$$\underbrace{\frac{1-e^{-(r+\delta-\alpha)x}}{1-e^{-(r+\delta-\alpha)L}}\overline{R}}_{A} - \underbrace{\frac{1-e^{-(r-\alpha)x}}{1-e^{-(r-\alpha)L}}\overline{R}}_{B} > \underbrace{\frac{1-e^{-(r+\delta)x}}{1-e^{-(r+\delta)L}}I}_{C} - \underbrace{\frac{1-e^{-rx}}{1-e^{-rL}}I}_{D}.$$

By Lemma 1, this inequality will hold if (i) $A \geq C$, (ii) $C > D$, and (iii) $A/B > C/D$.

To show that (i) $A \geq C$, rewrite this inequality as

$$\underbrace{\frac{r+\delta-\alpha}{1-e^{-(r+\delta-\alpha)L}}\overline{R}}_{A_1} \times \underbrace{\frac{1-e^{-(r+\delta-\alpha)x}}{r+\delta-\alpha}}_{A_2} \geq \underbrace{\frac{r+\delta}{1-e^{-(r+\delta)L}}I}_{C_1} \times \underbrace{\frac{1-e^{-(r+\delta)x}}{r+\delta}}_{C_2}$$

From (A7), we have that $A_1 \geq C_1$ for any time $T \geq T^c$; this includes time $\widehat{T}$, since $\widehat{T} \geq T^m \geq T^c$. Also, since for any $x > 0$ and $r > 0$,

$$\frac{d}{dr}\left[\frac{1-e^{-rx}}{r}\right] < 0,$$

we have that $A_2 > C_2$.

To show that (ii) $C > D$, it is sufficient to show that for any $L > x > 0$ and $r > 0$,

$$\frac{d}{dr}\left[\frac{1-e^{-rx}}{1-e^{-rL}}\right] > 0,$$

$$\overset{s}{\Leftrightarrow} \quad \frac{xe^{-rx}}{1-e^{-rx}} - \frac{Le^{-rL}}{1-e^{-rL}} > 0.$$

Since $L > x$, sufficient for the latter inequality is that

$$\frac{d}{dx}\left[\frac{xe^{-rx}}{1-e^{-rx}}\right] < 0,$$

$$\overset{s}{\Leftrightarrow} \quad (1-rx) - e^{-rx} < 0.$$

Finally, to show that (iii) $A/B > C/D$, it is sufficient to show that for any $L > x > 0$, $r > 0$ and $\delta > 0$,

$$\frac{d}{dr}\left[\frac{\dfrac{1-e^{-(r+\delta)x}}{1-e^{-(r+\delta)L}}}{\dfrac{1-e^{-rx}}{1-e^{-rL}}}\right] < 0,$$

$$\overset{s}{\Leftrightarrow} \quad L\left[\frac{1}{e^{rL}-1} - \frac{1}{e^{(r+\delta)L}-1}\right] - x\left[\frac{1}{e^{rx}-1} - \frac{1}{e^{(r+\delta)x}-1}\right] < 0,$$

$$\overset{\delta}{\Leftarrow} \quad \frac{L^2 e^{(r+\delta)L}}{(e^{(r+\delta)L}-1)^2} - \frac{x^2 e^{(r+\delta)x}}{(e^{(r+\delta)x}-1)^2} < 0.$$

Since $L > x$, sufficient for the latter inequality is that

$$\frac{d}{dx}\left[\frac{x^2 e^{(r+\delta)x}}{(e^{(r+\delta)x}-1)^2}\right] < 0,$$

$$\overset{s}{\Leftrightarrow} \quad 2e^{y} - 4 + 2e^{-y} - ye^{y} + ye^{-y} < 0, \qquad \text{where } y \equiv (r+\delta)x$$

$$\overset{y}{\Leftarrow} \quad e^{y} - ye^{y} - e^{-y} - ye^{-y} < 0,$$

$$\overset{y}{\Leftarrow} \quad y(e^{-y} - e^{y}) < 0.$$

□

Subsection 6.1: If CDM contracts cover just a single subproject at a time, Proposition 2 goes through unchanged, except that the low-hanging fruit problem will arise

only if the *first* subproject of a given project straddles the graduation time, i.e., if L is such that $T^c + L > G$.

Proof: In the competitive case, the assumption that CDM contracts are for one subproject at a time rather than for entire projects complicates the analysis much less than in the monopsony case. The reason is that, whereas a monopsonist Annex-1 investor chooses T^m partly ignoring the knock-on effects of its choice on successor subprojects to the first $m(T)$ that it undertakes, the host-country government will take any knock-on effects fully into account when choosing when to auction off a first subproject. In effect, then, it will still end up choosing the time T^c that maximizes its perceived present value of the entire project:

$$T^c \equiv \arg\max_{T \geq 0} e^{-(r+\delta)T} \widehat{V}(T). \tag{A17}$$

With this redefinition of T^c, Proposition 2 goes through unchanged, except that the low-hanging fruit problem will arise only if the first subproject of a given project straddles the graduation time, i.e., if L is such that $T^c + L > G$. To see why, note that the host-country government will never choose T^c such that the value $v(T^c)$ of the very first subproject taken alone is negative, since it could then do better by abandoning the first subproject and instead waiting until time $T^c + L$. But $v(T^c) \geq 0$ implies, by the identity $V(T) \equiv v(T) + e^{-rL}V(T+L)$, that

$$e^{-rT^c} V(T^c) \geq e^{-r(T^c+L)} V(T^c + L). \tag{A18}$$

By the single-peakedness of the $e^{-rT}V(T)$ function, this in turn implies that $T^* < T^c + L$.

Suppose now that the first subproject does *not* straddle the graduation time, so that $T^c + L \leq G$. In the case of Type-III projects, this results in a contradiction: it is not possible to simultaneously have $T^* < T^c + L \leq G$ and $T^* \geq G$. For all Type-III projects that the host-country government auctions off under the CDM, the first subproject therefore necessarily straddles the graduation time.

For Type-II projects, it *is* possible to have $T^c + L \leq G$, but single-peakedness of the $e^{-rT}V(T)$ function then implies that

$$e^{-rT^*} V(T^*) > e^{-r(T^c+L)} V(T^c + L) \geq e^{-rG} V(G). \tag{A19}$$

Combining the second of these inequalities with (A18) yields by transitivity that

$$e^{-r(T^c)} V(T^c) \geq e^{-rG} V(G), \tag{A20}$$

i.e., that no low-hanging fruit problem arises. It follows that $T^c + L > G$ is necessary (together with $T^c < T^\ell$) for a low-hanging fruit problem to arise. □

Subsection 6.1: If CDM contracts cover just a single subproject at a time, Propositions 3 and 4 go through unchanged when L is finite, except that the wording of the clauses must be slightly modified. The European form of the virtual-option clause, for example, becomes

> **If the time $T + L$ at which the current subproject ends extends beyond the time of graduation, the host-country government retains the right to undertake all successor subprojects 'virtually' starting from the time of graduation, by replicating the revenue and cost streams that would have accrued to the host-country government had it *physically* undertaken all successor subprojects from G rather than from $T + L$.**

and the American form must be modified analogously.

Proof: In the benchmark model, with q and I constant over time, implementing the clause at time G is straightforward. To replicate the revenue stream from undertaking all successor subprojects from G, the Annex-1 investor can simply transfer title to all remaining credits generated by the current subproject alone (since the host-country government already has title to all credits generated by its successor subprojects from $T + L$ onwards). To replicate the cost stream, the host-country government can pay the Annex-1 investor a sum of $\left[1 - e^{-r[(T+L)-G]}\right] \tilde{I}$ to cover the difference between the investment costs $e^{-r[(T+L)-G]} \sum_{n=0}^{\infty} e^{-rnL} I = e^{-r[(T+L)-G]} \tilde{I}$ that it will incur for all successor subprojects from $T+L$ onwards and the costs $\tilde{I}$ that it would have incurred had it undertaken those successor subprojects from G. Note that this payment, which can be rewritten as

$$\left[1 - e^{-r[(T+L)-G]}\right] \tilde{I} = \int_0^{(T+L)-G} e^{-rt} r \tilde{I}\, dt,$$

just equals the current subproject's remaining *annualized* cost.

In the monopsony case, the clause both restores optimal timing and prevents the low-hanging fruit problem. It does so by changing the Annex-1 investor's rents from starting the project at any given time T to

$$e^{-rT} \Big\{ \Big[V(T) - e^{-rm(T)L} V(T + m(T)L) \Big] - \Big[e^{-r(G-T)} V(G) - e^{-rm(T)L} V(T + m(T)L) \Big] \Big\}$$
$$= e^{-rT} V(T) - e^{-rG} V(G),$$

where the second term in brackets on the left-hand side is the value, discounted to T, of the virtual option, which in turn equals the full opportunity cost to the host-country citizens of having the $(m(T)+1)$-st subproject be pushed back from time G to time $T+m(T)L$.

In the competitive case, the clause prevents the low-hanging fruit problem by dissuading Annex-1 investors from bidding on any subproject until its value exceeds the discounted value of the option, i.e., until

$$v(T) \geq e^{-r(G-T)}V(G) - e^{-rL}V(T+L).$$

Combining this inequality with the identity $V(T) = v(T) + e^{-rL}V(T+L)$ shows that the earliest time at which an Annex-1 investor will bid on a subproject is T^{ℓ}, where by definition $V(T) \geq e^{-r(G-T)}V(G)$ and so no low-hanging fruit problem arises.

As was the case with infinite L, the European virtual-option clause fails to ensure full rent extraction by the host country in the monopsony case and fails to ensure optimal project timing in the competitive case. Both *are* again ensured by the American version of the virtual-option clause, which for when L is finite should read

> The host-country government retains the right to, at any time S of its choosing up to the time $T+L$ at which the current subproject ends, undertake all successor subprojects 'virtually,' by replicating the revenue and cost streams that would have accrued to the host-country government had it *physically* undertaken all successor subprojects at S rather than $T+L$. This right may be transferred at any time to a third party.

As with the European virtual-option clause, the clause could in the benchmark case be implemented at time S by simply having the Annex-1 investor transfer title to the remaining credits generated by the current subproject in return for a payment equal in present value to the current subproject's remaining annualized cost $[1-e^{-r\{(T+L)-S\}}]\tilde{I}$. From the point of view of an Annex-1 financial investor, the value of the option at S is then

$$\int_{S}^{T+L} e^{-r(t-S)}p(0)qe^{\alpha t}\,dt - [1-e^{-r\{(T+L)-S\}}]\tilde{I} = V(S) - e^{-r[(T+L)-S]}V(T+L), \tag{A21}$$

or $e^{-rS}V(S) - e^{-r(T+L)}V(T+L)$ when discounted to time zero at rate r.

Note now that, because the obligations an Annex-1 physical investor incurs through the virtual-option clause can only reduce its profits from a given subproject, no Annex-1 physical investor—whether monopsonist or competitive—will undertake a first subproject until the gross profits $v(T)$ from that project are positive. Equivalently, by the identity $e^{-rT}V(T) = e^{-rT}v(T)+e^{-r(T+L)}V(T+$

L), no first subproject will be undertaken before T such that $e^{-rT}V(T) > e^{-r(T+L)}V(T+L)$, which implies that $T+L > T^*$. But then from an Annex-1 financial investor's point of view, the value of the option will be maximized at either T^* or T, whichever comes later. This leaves the Annex-1 physical investor with negative net profits $[e^{-rT}V(T) - e^{-r(T+L)}V(T+L)] - [e^{-rT^*}V(T^*) - e^{-r(T+L)}V(T+L)]$ from undertaking the subproject at any $T < T^*$, and zero profits from undertaking it at any $T \geq T^*$. If we take this to imply that the host-country government can effectively choose T subject to $T \geq T^*$) even in the monopsony case, then the first subproject will always be undertaken at T^*. Moreover, auctioning off the virtual option will for all subprojects yield $V(T) - e^{-rL}V(T+L) = v(T)$, implying full rent extraction by the host country. □

Subsection 6.3: In the benchmark model, $T^u > T^*$ for abatement projects, while in a simple extension of the benchmark model that has the rate of credit generation decline exponentially with $T - t$ for sequestration projects, $T^u \gtreqless T^*$.

Proof: Let credit generation for sequestration projects decline at constant exponential rate λ, so

$$q(T, t) = qe^{-\lambda t},$$

where q is the initial rate of credit generation at the time T when the trees are planted.

In the thus extended benchmark model, we then have

$$V(T) \equiv \frac{p(0)qe^{\alpha T}}{r - \alpha + \lambda} - I \tag{A22}$$

$$V^u(T) \equiv \frac{p(0)qe^{\alpha T}}{r + \delta - \alpha + \lambda} - I, \tag{A23}$$

where $\lambda = 0$ for abatement projects, and $\lambda > 0$ for sequestration projects. Interior values of T^u are defined implicitly by

$$\frac{\partial e^{-(r+\delta)T}V^u(T)}{\partial T} = e^{-(r+\delta)T}\left[-\frac{r + \delta - \alpha}{r + \delta - \alpha + \lambda}p(0)qe^{\alpha T} + (r + \delta)I\right] = 0.$$

Applying the implicit function theorem, we have

$$\frac{dT^u}{d\delta} = -\frac{-\dfrac{\lambda}{(r + \delta - \alpha + \lambda)^2} + I}{-\dfrac{\alpha(r + \delta - \alpha)}{r + \delta - \alpha + \lambda}p(0)qe^{\alpha T}}.$$

If $\lambda = 0$, i.e., for abatement projects, the numerator on the right-hand side, and thereby the right-hand side as a whole, is positive, implying (since $\lim_{\delta \to 0} V^u(T) = V(T)$) that $T^u > T^*$. But if

$\lambda > 0$, i.e., for sequestration projects, the numerator may well be negative—particularly at low values of δ—implying that potentially $T^u \leq T^*$. □

Subsection 6.3: In the competitive case, an overdiscounting host-country government will strictly prefer to auction off a project at time T^c to undertaking it unilaterally at time T^u.

Proof: Since for an overdiscounting host-country government $e^{-(r+\delta)T}V(T) > e^{-(r+\delta)T}V^u(T)$ at all T, this must be true at $T = T^u$ as well. Also, by the definition of T^c, $e^{-(r+\delta)T^c}V(T^c) \geq e^{-(r+\delta)T^u}V(T^u)$. The result follows by transitivity.

Subsection 6.3: In the monopsony case with an overdiscounting host-country government, the Annex-1 investor's rents are in the benchmark model always maximized at some $T^m < T^u$.

Proof: The Annex-1 investor's rents from undertaking the project at any time $T < T^u$ are

$$R(T) = e^{-rT}\left[V(T) - e^{-(r+\delta)(T^u-T)}V^u(T^u)\right] = e^{-rT}V(T) - e^{\delta T}e^{-(r+\delta)T^u}V^u(T^u).$$

Differentiate w.r.t. T to get

$$\frac{dR(T)}{dT} = -re^{-rT}V(T) + e^{-rT}V'(T) - \delta e^{\delta T}e^{-(r+\delta)T^u}V^u(T^u).$$

Evaluating the derivative at T^u yields

$$\left.\frac{dR(T)}{dT}\right|_{T=T^u} = e^{-rT^u}\left[-rV(T^u) + V'(T^u) - \delta V^u(T^u)\right] \tag{A24}$$

We also know from the definition of T^u that

$$e^{-(r+\delta)T^u}\left[-rV^u(T^u) + V^{u\prime}(T^u) - \delta V^u(T^u)\right] = 0. \tag{A25}$$

Comparing (A24) and (A25) shows that the derivative of the Annex-1 investor's rents at T^u will be negative if and only if

$$-rV(T^u) + V'(T^u) < -rV^u(T^u) + V^{u\prime}(T^u),$$

But this is indeed the case, since, using (A22) and (A23), we can write

$$[-rV(T^u) + V'(T^u)] - [-rV^u(T^u) + V^{u\prime}(T^u)]$$

$$= \left[-r\left\{\frac{p(0)qe^{\alpha T}}{r-\alpha+\lambda} - I\right\} + \alpha\frac{p(0)qe^{\alpha T}}{r-\alpha+\lambda}\right] - \left[-r\left\{\frac{p(0)qe^{\alpha T}}{r+\delta-\alpha+\lambda} - I\right\} + \alpha\frac{p(0)qe^{\alpha T}}{r+\delta-\alpha+\lambda}\right]$$

$$= (r - \alpha)p(0)qe^{\alpha T}\left[\frac{1}{r + \delta - \alpha + \lambda} - \frac{1}{r - \alpha + \lambda}\right] < 0.$$

Moreover, evaluating the Annex-1 investor's rents themselves at T^u yields

$$R(T^u) = e^{-rT^u}\left[V(T^u) - V^u(T^u)\right],$$

which is positive because the term in brackets is positive. □