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Assessing Investment in Future Landsat Instruments

The Example of Forest Carbon Offsets

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RESOURCES
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Assessing Investment in Future Landsat Instruments: The Example of Forest Carbon Offsets

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Abstract

We extend the theory of quality-adjusted expenditure indices to estimate benefits from public investment. In particular, we model the selection of new instruments (in the form of remote-sensing devices) to enhance the longest-operating U.S. satellite-based land-observing program, Landsat. We then apply the model to the use of Landsat in measuring global forest carbon sequestration. Improving measurement of the role of forests in storing carbon has become a prominent concern in climate policy. By characterizing the value of Landsat data in forest measurement, the expenditure function allows us to help inform public investment decisions in the satellite system. The expenditure function also makes explicit the sensitivity of the selection of instruments for the satellites to the value of Landsat information, thus linking instrument choice explicitly to policy design.

Key Words: value of information, satellite data, forests, carbon, sequestration, Landsat

JEL Classification Numbers: Q0, Q2, O3

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Molly K. Macauley and Jhih-Shyang Shih*

1. Introduction

A concern of government decisionmakers responsible for funding new technology is whether the investment will eventually "pay off" for the taxpayer. We model the selection of new instruments (remote sensing devices) for the longest continuously operating U.S. satellite-based land-observing program, Landsat. Since the launch in 1972 of the first in a series of satellites, the program has continued to provide data about natural and environmental resources in the United States and other countries from the unique vantage point of space. At various times in the history of the program, its managers have faced the question of whether to invest in new instruments to enhance the program's effectiveness and the benefits of its data.

Our model is intended to help answer this question. We extend the theory of quality-adjusted expenditure indices to develop a conceptually rigorous means of estimating public benefits from new technology. We express the benefits in terms of the economic value of the information provided by Landsat. Because we characterize the prospective benefits tomorrow from an investment decision made today, we explicitly incorporate several sources of uncertainty in the model.

We first develop the general model and then illustrate how it works by applying it to a specific case: the role of Landsat observations in the management of forest carbon sequestration. The capacity of forests to store carbon is quantitatively significant both scientifically, as part of the global climate system, and from the perspective of public policy, as part of U.S. and international discussions of approaches to manage greenhouse gas emissions. As a policy matter, the U.S. Energy Information Agency (EIA), Environmental Protection Agency (EPA), Congressional Budget Office, and other agencies estimate that the management of forest carbon storage, often called "forest offsets," can reduce the economic cost of stabilizing atmospheric

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concentrations of greenhouse gases by as much as 80 percent (U.S.EIA 2009; U.S.EPA 2009; Congressional Budget Office 2009).The studies emphasize, however, that realizing these savings depends critically on improved information about the size, geographic distribution, and changes over time of physical quantities of forest carbon. Landsat observations are a source of data to inform these offset measures.

This use of Landsat data is the focus of our paper. We first develop an expenditure-based model to characterize the economic cost of various climate policies and the importance of forest carbon sequestration. We then use a standard value-of-information approach to derive a value for Landsat data from the economic value of forest carbon. Hence the relationships we model are expenditures for climate management and forest carbon, the desirability of good data about forest carbon, and the contribution of Landsat data. We then consider how a new type of Landsat instrument can change the derived value of Landsat data.

This approach allows us to ascribe prospective value to Landsat data in different climate management scenarios under policy consideration. We use technical and cost information provided by Landsat managers for current Landsat instrumentation and the next generation of instruments, hyperspectral imagers. We consider the period 2022–2026, during which the U.S. Geological Survey (USGS) expects to launch the hyperspectral imager and begin operations. We combine this information with climate policy scenarios and related economic data about forest sequestration projected for the same time period. These scenarios and data are from widely used EIA analyses.

The approach tightly couples the Landsat instrument-planning decision with relevant public policy choices. The climate management scenarios vary markedly in the trade-off they prescribe between cutting emissions directly and allowing use of forests to sequester carbon. We find that in policy scenarios allowing the use of international forest offsets, and conditional on several key assumptions about the contribution of Landsat to forest carbon measurement, the estimated benefits of Landsat data are on the order of $1 billion annually (in discounted present value).The benefits are smaller—and in some cases negative—in scenarios that allow only a limited role or no role at all for international forest offsets because in these cases, the measurement capability of Landsat for observing global land use is of less use. Negative benefits result when the benefits of the data do not outweigh the annualized cost of the Landsat system.

We emphasize that the EIA analyses assume the emergence of a market-like approach to managing greenhouse gas emissions. If a regulatory approach is taken instead (thus, physical quantities of GHG emissions are controlled without market incentives), our model can be interpreted as illustrating the shadow value of carbon sequestration (that is, the implied value of using forests to sequester carbon as a means of countering the harm from GHG emissions).

We also emphasize that we focus only on use of Landsat data for forest measurement and exclude other valued uses of the data. To our knowledge, no economic research estimates the value of Landsat data in its myriad other uses. Taking account of multiple uses of Landsat data would increase Landsat benefits. We return to this problem of economies of scope in Landsat data in our conclusions.

2. Background

2.1. The Landsat System

Under the leadership of the USGS, the Landsat system is the oldest continuously operating program for collecting and making publicly available observations of Earth's natural and environmental resources from the vantage point of space. Landsat data have many applications to natural and environmental resource issues (see U.S. Office of Science and Technology Policy 2007; Macauley 2009). Landsat observations of land use are a mainstay of forest area estimates (Macauley et al. 2009; Fagan and DeFries 2009; GOFC-GOLD 2007). Notably, the Food and Agricultural Organization of the United Nations, responsible for periodic inventory of global forests, has begun to include Landsat data in the next inventory (FAO 2009).

The system has traditionally consisted of one or more satellites and their instruments, as well as ground systems, operations, and data management. An attribute of the system featured in this paper is selection of instruments for the satellites. The instruments are the heart of the system; their technical specifications determine the characteristics and ultimate usefulness of the imagery. These characteristics include spatial, spectral, and temporal resolution. At present, two Landsats are operating, and these carry sensors optimized for several spectral regions of importance in understanding land use.[1]

One of the challenges in the history of the program has been selection of instruments over time, as satellites, their instruments, or both cease operation and replacement satellites are planned (for example, see discussion in U.S. Office of Science and Technology Policy

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[1] Technical details about these sensors are available at http://landsat.gsfc.nasa.gov/about/technical.html (accessed January 2010).

2007).Instrument design and selection involve a complex balancing of the desire for data continuity—by which attributes of previous data match those of the new data, enabling temporal comparisons of land use—and the desire for enhanced capability. Enhancements usually include changes in spatial, spectral, or temporal resolution.

Following conversations with the USGS, the new enhancement we model to the existing Landsat system is a hyperspectral imager planned for launch on Landsat 10 in fiscal year 2021. Hyperspectral imaging "slices" the electromagnetic spectrum into a very large number of discrete spectral bands, usually more than 100 (Strand et al. 2007). In assessments of the instruments best suited to improve forest measures, many experts have emphasized the desirability of radar and lidar (light detection and ranging), techniques that help to estimate forest volume (for example, see Fagan and DeFries 2009; GOFC-GOLD 2008). Among many applications of hyperspectral imaging, it could increase the ability to identify tree species in forests (Strand et al. 2007; Jet Propulsion Laboratory 2009; Fagan and DeFries 2009), thus complementing the existing Landsat observations about the area extent of forests. The imager could also permit improved monitoring of plant health, including conditions conducive to wildfires and pests, and enhance understanding of carbon sequestration among different types of ecosystems when these vary by plant species (Jet Propulsion Laboratory 2009).

2.2 The Role of Information in the Economics of Forest Carbon

Forests store carbon by taking in carbon dioxide from the atmosphere during respiration. The trees draw the carbon atoms into the plant cell and release oxygen back into the atmosphere. Trees are particularly efficient at sequestering carbon. This sequestration plays a large role in the global carbon cycle. By contrast, when forests are removed or damaged (by wildfire, pests, drought, or other occurrences), carbon is released (some portion remains stored in furniture and other timber products, however). Estimates of emissions from forest removal range from 7 percent to 30 percent of all greenhouse gas emissions (Denman 2007; Houghton and Goetz 2008; van derWerf et al. 2009).[2]

The economic significance of forest carbon sequestration is large. According to estimates by the EIA, EPA and Office of Management and Budget, the annual economic value of forest

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[2] Emissions of different types of greenhouse gases from different sources are commonly converted to units of carbon dioxide equivalent based on the potential of each gas to contribute physically to global warming.

carbon offsets could be significant. The EIA estimates the value at about $60 billion annually by 2030 under some policy scenarios.[3] Without forest offsets, the cost of greenhouse gas management expressed in terms of the discounted value of loss in U.S. gross domestic product (GDP) could be about 50 percent larger, increasing from about 0.2 percent to 0.3 percent of cumulative real GDP between 2012 and 2030 (U.S. EIA 2009).

The agencies emphasize that they base these estimates on the assumption that physical forest carbon sequestration capacity can be accurately measured over time and around the world, but at the same time, they express concern about whether adequate measurement and monitoring is in fact attainable (U.S. EPA 2009; U.S. EIA 2009; U.S. GAO 2008;Gorte and Ramseur 2008; Congressional Budget Office 2009; Sheikh and Gorte 2009).Four widely recognized measurement issues are of particular concern. One is the requirement for better baseline estimates and monitoring of changes in the basic physical carbon sequestration capacity of forests. Related issues pertain to changes in sequestration due to influences that experts refer to as leakage, permanence, and additionality.

We next discuss these four concerns because we assume they are alleviated by Landsat data. This assumption underlies how we ascribe value to Landsat in section 4.

Measurement

Remote sensing cannot directly measure the amount of carbon in forests, but correlative remote-sensing inventory data and the use of allometric equations yield estimates based on observations of forest area, growing density, and biomass (GOFC-GOLD 2007; Fagan and DeFries 2009). Figure 1 shows these relationships. Landsat provides information about the area variable in the equations. As noted above, radar and lidar are usually required for measures of forest density (structure and height). Allometric equations and field measurement provide estimates of biomass. Measurement accuracy is required for two purposes: to help scientists understand the global carbon cycle and to satisfy requirements of regulators and other parties using forests to offset greenhouse gas emissions. Table 1 summarizes the offset measurement protocols. Small numbers of hectares of forest have required airborne LIDAR instruments to obtain the required accuracy.

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[3] See U.S. EIA 2009, Table ES-1, multiplying domestic and international offset quantities by estimated domestic and international offset prices for 2030.

Figure 1. Allometric Expression for Forest Carbon Stock

Symbol	Variable	Dimensions
A	Area	Hectare
D	Density of growing stock	Cubic meters per hectare
B	Allometric biomass ratio	Megagrams per cubic meter
C	Carbon concentration	Megagrams per megagrams

Multiplied together, the four variables equal a stock of megagrams of carbon

Source: Waggoner 2009

Table 1. Selected Standards for Accuracy and Precision of Forest Carbon Data

Source	**Standard type**	**Users**	**Level of accuracy/precision (metrics are source specific)**
Forest Project Protocol http://www.climateactionreserve.org/how/protocols/adopted/forest/development/	Voluntary greenhouse gas offset reporting protocol	Offset suppliers, offset purchasers	For projects: Up to 5% sampling error with 90% confidence level, no confidence deduction needed. Between 5% and 20% sampling error with 90% confidence level, amount over 5.1% confidence deduction required. At 20% sampling error with 90% confidence level, 100% risk contribution required.
Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2007: Land Use, Land Use Change, and Forestry http://www.epa.gov/climatechange/emissions/downloads09/LULUCF.pdf, 7–19	Government data collection project	Policymakers, scientists	In 2007, 910.1 Tgcarbon dioxide (CO_2) equivalent fluxed from U.S. forestlandswith an uncertainty range of +/- 19%.
Chicago Climate Exchange Project Guidelines: Forestry http://www.chicagoclimatex.com/docs/offsets/CCX_Forestry_Sequestration_Protocol_Final.pdf, 31	Voluntary greenhouse gas offset reporting protocol	Offset suppliers, offset purchasers	Accurate inventory data is +/- 10% of the mean estimated CO_2 sequestration at 90% confidence level.
*General and Technical Guidelines for the Voluntary GHG Reporting (1605(b)): Forestry Appendix*http://www.usda.gov/oce/global_change/Forestryappendix.pdf, 3	Government-sponsored voluntary greenhouse gas offset reporting protocol	Policymakers, scientists, offset suppliers, offset purchasers.	Best accuracy: +/-10% of true value of forest carbon. Adequate accuracy: +/-20% of true value of forest carbon. Marginal accuracy: +/-30% of true value of forest carbon. Inadequate accuracy: higher than +/- 30% of true value.

Reducing Greenhouse Gas Emissions from Deforestation and Degradation in Developing Countries: A Sourcebook of Methods and Procedures for Monitoring, Measuring and Reporting http://www.gofc-gold.uni-jena.de/redd/sourcebook/Sourcebook_Version_July_2009_cop14-2.pdf, 75, 102	Ad-hoc REDD (Reducing Emissions from Deforestation and Forest Degradation) working group methodological descriptions	Policymakers, scientists, offset suppliers, offset purchasers	Research data: uncertainty level of 20% or less (95% confidence equal to 20% of the mean or less). Conservativeness: To avoid overestimation of emissions reduction, measurements are multiplied by a category-specific conservativeness factor.
2006 IPCC Guidelines for National Greenhouse GasInventories http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, 4–19	Reporting standards for national greenhouse inventories	Policymakers, scientists, offset suppliers, offset purchasers	Uncertainty estimates (percent of mean) for forest carbon factors: Wood density: 10–40%; natural losses for industrialized countries: 15%; industrialized-country growing stock, non-industrialized growing stock: 30%; annual increment in managed forests (industrialized countries): 6%; wood removals for industrialized countries: 20%.
American Carbon Registry™ Forest Carbon Project Standard http://www.americancarbonregistry.org/carbon-accounting/ACR%20Forest%20Carbon%20Project%20Standard%20v1%20March%202009%20FINAL.pdf, 26	Voluntary greenhouse gas offset reporting protocol	Offset suppliers, offset purchasers	+/- 10% mean estimated CO_2 sequestration at 90% confidence level.
EPA *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology: Reforestation/Afforestation* http://www.epa.gov/climateleaders/documents/resources/draft_reforestation_offset_protocol.pdf, 12	Government-sponsored voluntary greenhouse gas offset reporting protocol	Policymakers, scientists, offset suppliers, offset purchasers	+/- 10% precision of estimated CO_2 sequestration at 95% confidence level.

Source: Macauley et al. 2009

Leakage

The problem of leakage could prevent a forest carbon market from functioning effectively to offset greenhouse gas emissions. Leakage occurs when reduced deforestation in one area drives deforestation to another area. Forecasts of how much forested area may be protected for sequestration may be incorrect if it is assumed that no leakage occurs. Murray et al. (2004) estimate leakage at 10–90 percent for various activities in the United States. Without adequate monitoring of forests in all countries, leakage could undermine efforts to stabilize greenhouse gas emissions.

Additionality

The objective of most proposals to assign credit to manage forest carbon is to reward actions that would not have happened otherwise—that is, actions that are additional to "business as usual." Additionality requires an initial measurement, or baseline inventory, at a point in time, as well as periodic monitoring to observe changes in the inventory.

Permanence

Changes in forests from logging; conversion of forested land to agriculture; or events such as wildfires, pest outbreaks, and drought affect the long-term permanence of carbon sequestration. Some forest carbon management proposals are designed for discounting or rental of forest assets to account for the possibility of their impermanence (Pffaf et al., 2000; Kim et al. 2008). For example, if an electric utility had purchased forest carbon to offset some of the utility's greenhouse gas emissions, the utility could rent the forest; if the forest underwent change, the offset commitment could continue to be satisfied by transferring the rental to another forest. Monitoring forest change is key to permanence.

Many experts consider these measurement problems to be so severe as to limit substantially the role of forest carbon sequestration in climate management. The U.S. Government Accountability Office expresses several concerns, noting that "ensuring the credibility of carbon offsets poses challenges because of the inherent uncertainty in measuring emissions reductions or sequestration relative to a projected business as usual scenario" (U.S. GAO 2008, p. 37). Congressional proposals include special provisions that recognize these problems. Legislation passed by the U.S. House of Representatives (H.R. 2454) and proposed in the U.S. Senate (S. 1733) limit the total allowance of offset credits and discount international offsets by 25 percent (on a per unit basis[4]).Both the House and the Senate provisions establish an Offset Integrity Advisory Board. As described in the Senate provisions, the Board will establish "methodologies to address the questions of additionality, activity baselines, quantification methods, leakage, uncertainty, permanence, and environmental integrity" (S.1733, Section 731).

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[4] Companies must purchase more international offsets than domestic offsets to get credit in the offset market; the ratio is 1.25 international offsets to 1 domestic offset.

2.3 Economic Value of Information

These concerns demonstrate that the supply of forest carbon offsets depends on high-quality information about global land use and changes in land use. Determining supply requires measures of physical quantities, including baseline measures and periodic changes; observations of natural influences on forest health; economic influences (the wood products market, logging and timber, agriculture, fuelwood); and ecosystem services (watershed protection, biodiversity). Because Landsat is the longest-running program to observe global land use, the Landsat archives and the continuation of Landsat observations could provide global snapshots overtime to help policymakers establish baseline inventories and monitor leakage, additionality, and permanence.

Ascribing economic value to the observations is difficult, however. How much of the value of offsets is attributable to the observational information about them? Here, we face a gap in understanding the value of Landsat as a source of observational information, although the scientific and applied uses of Landsat data are extensive. Missing are good benchmarks of the value of the data. The problem is common to information—for example, one can ask the same question as to how useful are census data, or data on air quality, or data on the spread of disease.

In the absence of estimates of the economic value of Landsat, we draw from the existing literature on the value of information. The usual approach in this previous work is to link the value of information to its relevant market. A variety of statistical, heuristic, and other approaches are used, often limited by the availability of data. This literature is a wide-ranging mix of studies of the role of information in different situations, ranging from energy markets to agriculture. None of these studies addresses land remote-sensing observations (although many focus on weather data).In summarizing the findings, Nordhaus (1986, 130) concluded:

> …all of the studies I know of the value of perfect information find its value to be on the order of one percent of the value of output. For example,… one study found that if you halve the standard error of precipitation and temperature, say from one percent to half percent, or one degree to one-half a degree, you get an improvement in the value of the output on the order of 2 percent of the value of wheat production. A study of cotton gave the same order of magnitude. I have looked at a number of studies in the area of nuclear power and energy, trying to determine the value of knowing whether nuclear power is ever going to pan out. Again, perfect information is worth on the order of one percent of the value of the output. From these kinds of studies, then, we find the value of information is not zero, but it is not enormous, either.

In valuing Landsat data for forest carbon, we assume a value of information in the range noted by Nordhaus. This is a key assumption in our approach, and we return to it in discussing our results.

3. Approach

We draw from the discussion above to model the role of Landsat as a source of information in forest carbon management. We use highly detailed and widely cited analyses by the U.S. EIA (2009; the EIA notes that is analyses also incorporates information from U.S. EPA (2009)). The EIA carried out the analyses for the purpose of evaluating the leading congressional proposals for climate management policy. These analyses estimate the cost to the U.S. economy, in terms of GDP, of stabilizing atmospheric concentrations of greenhouse gases. The studies are built on several scenarios, all based on using a market approach to reduce greenhouse gas emissions and enhance use of biogenic sequestration. The approach, familiarly known as cap and trade, allows utilities to trade emissions permits for which government sets an overall physical limit or cap.

We use three scenarios in these analyses to illustrate the value of forest carbon and, in turn, the value of information as provided by Landsat about forest carbon. The scenarios include a “high offset,” “no international offsets,” and “basic” case. The scenarios differ markedly in the use of offsets, thus allowing an opportunity to compare different assumptions about offsets.[5]

Figure 2 illustrates the model. Dark-shaded boxes show data, light-shaded boxes show the key assumptions, and the white boxes show model outputs. The model begins with EIA data on the physical quantities and estimated prices of offsets and allowed emissions. Together, these measures give estimated expenditure on achieving the policy goal of stabilizing atmospheric concentrations. As emphasized earlier, forest carbon offsets serve to reduce the cost of stabilization. We assume that a portion of the value of forest carbon offsets is attributable to observational information about forests. We base this key step on the approach to derived value of information described earlier.

We assume that the value of information increases with enhanced observational capability due to investment in new technology (the hyperspectral imager). Previous literature on

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[5] To the extent that the costs also represent costs under nonmarket rules, such as regulations to manage climate, this approach remains relevant; the values of forest carbon are “shadow values.”

adoption rates of new technology in a wide range of consumer goods, production technologies, and other markets find that adoption generally takes the form of an “s-shaped” curve that depicts initially somewhat slow adoption followed by somewhat faster adoption. Macauley et al. (forthcoming) show this s-pattern in the growing use of remote-sensing data over time. They find that use of new or enhanced data is at first slow as data are validated, verified, and used in scientific study or algorithm development. Use then spreads more rapidly among a variety of applications of the data. Halsing et al. (2004) also find evidence of this pattern in adoption of digital geospatial data in mapping. Following these results, we use an s-shaped adoption rate to describe the adoption of the new data from the new imager. The assumptions about the value of information and adoption rate then allow us to allocate a portion of the value to observational information. We then adjust the expenditure function by this value and, in the final steps, derive the index and net benefit.

3.1 Welfare Improvements

The heart of the model is the development of quality-adjusted cost indices, based on and analogous to consumer price indices. In using this approach as our analogy, these quality adjustments include changes in the data characteristics of Landsat instrumentation. The index formulation is an extension of an approach pioneered by Bresnahan (1986), who developed an index for comparing welfare gains from *past* investment in new technologies. Bresnahan’s index builds on the idea behind consumer price indices in which, to the extent possible, quality differences among goods and services are incorporated.[6] The index is useful to describe derived demand rather than final demand for a product. For example, Bresnahan applies the index to consumer demand for new computer technologies as inputs into financial and other sectors of the economy. By analogy, the model here is applied to derived demand for Landsat data as an input into the management of climate, through the value of Landsat in informing forest carbon offset markets.

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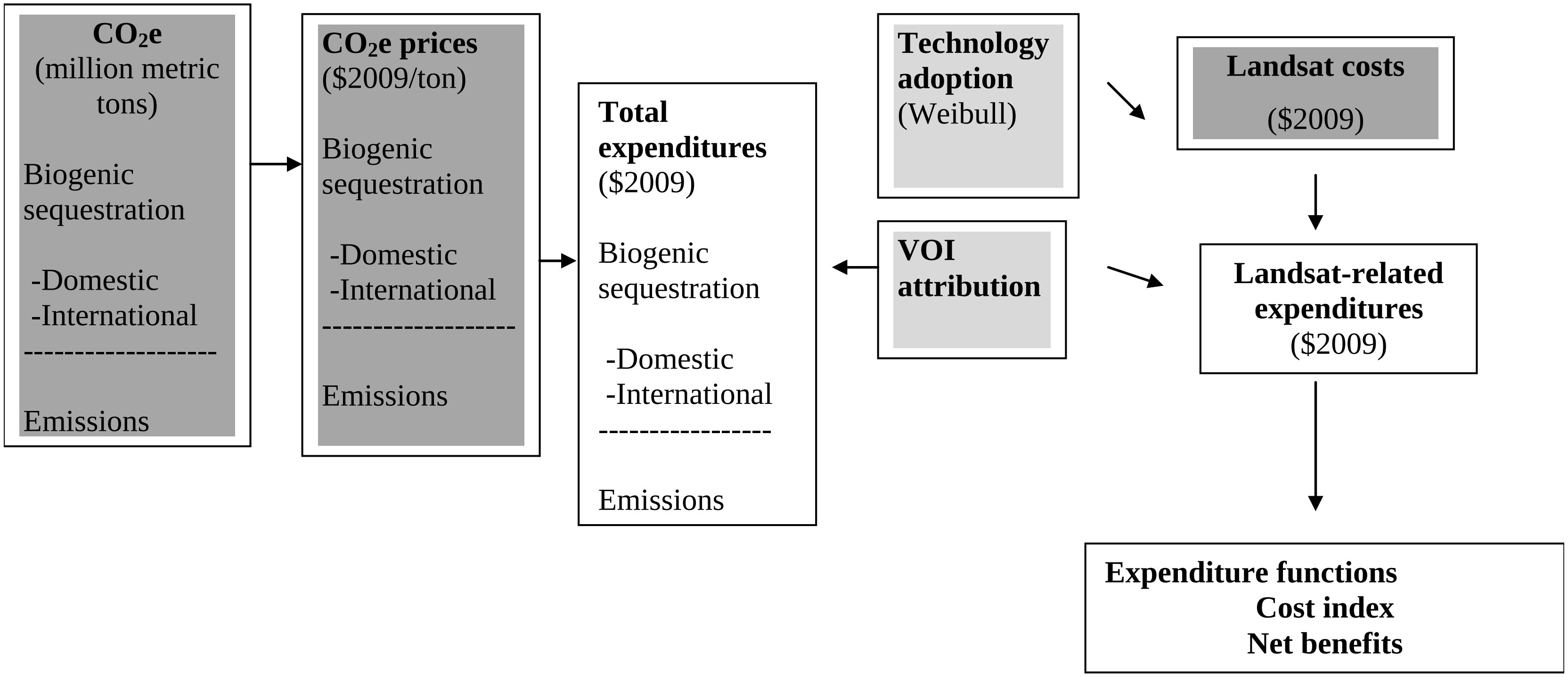
[6] An advantage of an index-based approach is that under certain general mathematical assumptions, the index is a function only of observed costs, adjusted for quality differences, and the share of expenditure represented by the product in total expenditures.

Figure 2. Illustration of the Model



Notes: CO_2e=carbon dioxide equivalent; VOI=value of information

Following Macauley et al. (2002) and Macauley and Shih (2007), we extend Bresnahan's approach to make the index prospective and evaluate the potential future gains from investment in Landsat. This adjustment allows for gradual diffusion of a new technology. A key feature in this extension is expressing the model's parameters as probability distributions to reflect uncertainty over future or estimated parameter values for both new instruments on Landsat and conventional, or "defender" technology (the status quo instruments).Testing the model includes shifting parameter locations to assess the robustness of assumptions about uncertain parameters.

The output gives an index that can be used to indicate economic performance of prospective investment in new technologies. In this way, the index can be a useful tool for decisionmakers. The output also includes the discounted present value of expected benefits, an understandable and meaningful measure to communicate the potential value of Landsat to decisionmakers.

Expression (1) below underlies the cost index given in (2).In (1), C^{*dt} is the minimum cost of achieving "utility" u^{dt}, or the socially optimal combination of conventional Landsat instruments expressed relative to the cost of u^{dt} after the investment in a new instrument ("N") that brings about reductions in cost (or increases in its social benefits) associated with use of the information provided by the instrument. Similarly, C^{*I} is the cost of achieving utility u^1 under the investment scenario with conventional costs W^{dt} relative to the cost of the instrument with post-innovation costs W^N.

$$C^{*dt} = \frac{E^*(u^{dt}, P^{dt}, W^{dt})}{E^*(u^{dt}, P^I, W^N)} \text{ and } C^{*I} = \frac{E^*(u^I, P^{dt}, W^{dt})}{E^*(u^I, P^I, W^N)}. \qquad (1)$$

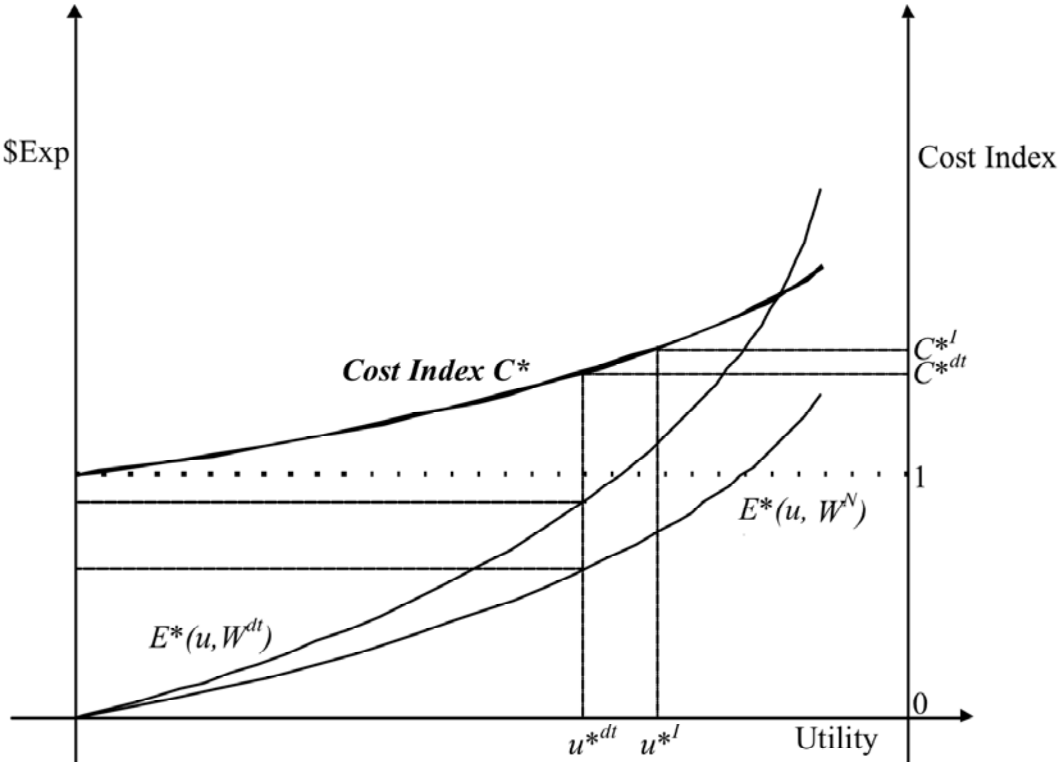
Because an innovation is assumed to be adopted gradually—and in this case, our interpretation is the adoption in use of data from a new instrument—the quality-adjusted cost of a new instrument is a combination of use of the new and conventional instruments such that $W^N = \rho W^I + (1-\rho)W^{dt}$ where ρ is the adoption rate of the new instrument and W^I is its cost when adopted. Prices P of other goods and services—in our case, expenditures on other technologies to control greenhouse gas emissions—can change over time, but it is assumed that they are unaffected by the innovation: $P^{dt} = P^N$ at all times. Manipulation of (1) based on cost index theory (see Caves et al. 1982) gives the index in (2):

$$\tfrac{1}{2}\ln\left(C*^{dt}\times C*^{I}\right)=\left(\tfrac{1}{2}(s^{dt}+s^{I})\cdot\ln\left(\frac{W^{dt}}{W^{N}}\right)\right). \tag{2}$$

The terms $s^{dt} + s^{I}$ give, respectively, forest offset-related information expenditures as a share of other expenditures (TE) under the baseline and investment-in-new instrument scenarios. These expenditure data serve as "weights" in the index. The monetary value of the investment is just the product of predicted TE times the exponent of the cost index.

Figure 3 shows the relationship among the expenditure functions and cost indexes. A welfare-enhancing innovation lowers consumers' costs of achieving a given level of utility, shifting the expenditure function downward from $E*(u,W^{dt})$ to $E*(u,W^{N})$. The vertical distance between the two curves depends on the share of forest offset–related information costs in total expenditures; their ratio is given by $C*$. Given a welfare-enhancing innovation I, consumers' optimal utility rises to $U*^{I}>U*^{dt}$. With separable utility and other prices unaffected, the relative cost to achieve $u*^{I}$ with higher baseline prices W^{dt} versus reduced, post-innovation prices W^{N} exceeds the relative cost to achieve $U*^{dt}$.

Figure 3. Expenditure and Cost Index



3.2 Adoption of New Technology

As noted above, we assume that adoption of data from a new instrument first requires a period of verification, validation, and, often, additional algorithm development, before these data are used for decisionmaking. An s-shaped Weibull process is often used to measure the time path of adoption, and Macauley et al. (forthcoming) have found that the Weibull fits growth in use of Landsat data over time. From the Weibull, adoption increases monotonically with time according to equation (3):

$$F(t) = 1 - \exp(-\lambda t^{\gamma}) \tag{3}$$

In (3), t is time in years; λ is a scale parameter $0 < \lambda < 1$, having the interpretation of a hazard rate (which is therefore assumed to be constant); and $\gamma > 0$ is a shape parameter. Different pairs of λ and γ give differently shaped curves. In general, larger values of λ imply a faster adoption rate. Larger values of γ will delay the time at which the inflection point occurs. The transition to the new hyperspectral instrument is planned by USGS to occur during the period 2022–2026, with the launch of the new imager in 2021.

3.3 Uncertainty

A key feature of our model is explicit incorporation of uncertainty. To characterize uncertainty, we use a standard approach based on Bayesian probability and Monte Carlo techniques to predict values.

In the case of data about the costs of Landsat, the design, hardware, engineering, and operations of the system draw from previous experience in the Landsat program. Even so, some uncertainty about these costs may be reasonable to assume given the widely acknowledged and documented complexity of cost estimation in a large variety of engineering projects (for example, see Quirk and Terasawa 1986;Terasawa et al. 1989;U.S. GAO 2004; see also Macauley 2008).We use the point estimates from the data as location parameters of probability distributions.

In the case of the data about the physical quantity and prices of emissions and sequestration, the EIA analyses from which we draw these data make clear that the models and assumptions are based on best available knowledge and the EIA’s own modeling assumptions. As in our treatment of Landsat costs, we use the point estimates from the data as location parameters of probability distributions.

We use triangular distributions for which the point estimates are the mode and the lower and upper bounds are 10 percent below and above the mode, respectively. The triangular distribution is often used to describe a population for which there are limited sample data but some understanding exists of the relationship between variables. (For example, this distribution is often used in simulating business decisionmaking and project management.) Although using some arbitrary assumptions is unavoidable given the data and their limitations, the resulting model is transparent and allows exploration of alternative assumptions.

4. Data and Assumptions

The time period for our analysis is 2022–2026. During this period, the USGS plans to launch Landsat 10 with a hyperspectral imager. We use data provided by the USGS about Landsat 9, with instruments similar to the existing Landsat, and Landsat 10 to represent our incumbent and new technologies. The data include cost estimates of developing and building flight hardware and software, ground system development, and launch. These costs are incurred pre-launch and at launch. The data also include the costs of post-launch technical support, operations, and data management.

The cost data from the USGS are for each fiscal year in which the costs are incurred, consistent with budgeting procedures. However, the benefits from the satellites occur after launch, during operations. We want to place all costs into the operating period to provide a basis for comparing costs and benefits. To do this, we treat the pre-launch and launch expenses as fixed costs that are incurred much like capital costs of investment in new plant and equipment. Following standard procedure, we place these on a per-period basis using a capital-recovery factor based on the operating life and an interest rate. In other words, we treat pre-launch costs as a loan, and we repay the loan during the operating years.[7]

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[7] We use expression (1) as the capital recovery factor (CRF; see Meyer et al. 1965):

CRF = $\{(i(1+i)^n) / ((1+i)^n - 1)\}$, where i is the interest rate and n is the life in years. For our base case, we use $i = 3$ percent, which is approximately the NASA inflation factor. The USGS estimates the nominal lifetime of each Landsat to be 10 years, thus we set $n = 10$.

The EIA data we use include the total covered emissions (million metric tons), biogenic domestic and international offsets (million metric tons), and prices (per million metric ton) of carbon emitted (in the case of emissions) or sequestered (in the case of offsets).The EIA analyses are among the most detailed and widely cited; other studies, such as those by U.S. EPA (2009), Anger et al.(2009), and Ihle (2009), take a similar approach.

4.1 Scenarios

The details of policy approaches to offsets remain speculative. The Copenhagen Accord resulting from the most recent Conference of the Parties to the United Nations Framework Convention on Climate Change in December 2009 represented limited international agreement to include provisions to encourage management of forests to reduce emissions from deforestation and degradation. If and how these provisions will ultimately be implemented in public policy is unclear. The EIA scenarios we select allow us to vary in the role of offsets and illustrate a range of results.

The three scenarios are EIA’s “basic” case, “high offset” case, and “no international offsets” case. In the basic case, the EIA assumes use of low-emissions energy technologies and allows regulated entities to “bank” emissions allowances for use in future years. In this case, the EIA also “assumes that the use of offsets, both domestic and international, is not severely constrained by cost, regulation, or the pace of negotiations with key countries covering key sectors” (EIA 2009, viii). The high offsets case relies heavily on offsets “without regard to possible institutional or market impediments” (EIA 2009, viii).In the case of no international offsets, offsets are limited to those within the United States, representing “an environment where the use of international offsets is severely limited by cost, regulation, and/or slow progress in reaching international agreements or arrangements covering offsets in key countries and sectors” (EIA 2009, viii).

The upper and lower panels of Table 2 summarize the data for 2020 and 2030, respectively, in the EIA scenarios. In all the scenarios, total covered emissions decline between 2020 and 2030 as the United States is assumed to reduce emissions at increasingly stringent rates to stabilize concentrations of emissions (rows a and f).Domestic prices per ton of emissions rise over time as emissions become increasingly more expensive to control (rows d and i). As a result, both domestic and international offsets become more attractive, and physical quantities increase between 2020 and 2030 (rows c and h) in two of the scenarios. The quantity of domestic offsets is highest in the case of no international offsets because the offsets market is restricted to domestic sources only. The quantity of international offsets is highest in the case of high offsets, where the supply is assumed to be larger and prices lower in the rest of the world than in domestic offsets markets. In the case of no international offsets, the zero entry in the table (last column in rows c and h) depicts a scenario in which only domestic offsets are allowed. The last row in each panel of the table shows the value of domestic and international offsets as a share of the total market (emissions plus offsets).

Table 2. Information about climate scenarios, 2020 and 2030

	Year 2020			
		Basic case	High offsets case	No international offsets case
a	Total covered emissions less offsets (million metric tons, mmt)	4,254	4,217	4,409
b	Domestic biogenic offsets (mmt)	251	161	385
c	International offsets (mmt)	966	1,305	0
d	Prices (metric ton)			
	Domestic	32	21	52
	International	25	16	42
e	Share of offsets in total market	.15	.17	.07
	Year 2030			
		Basic case	High offsets Case	No international offsets case
f	Total covered emissions less offsets (mmt)	2,739	3,573	3,107
g	Domestic biogenic offsets (mmt)	448	301	596
h	International offsets (mmt)	1,320	1,470	0
i	Prices (metric ton)			
	Domestic	65	42	106
	International	23	34	85
j	Share of offsets in total market	.17	.21	.13

Source: U.S.EIA 2009, Table ES-1

4.2 The Value of Landsat Information

Landsat provides a key part of the data required for estimating forest carbon sequestration. Remote-sensing and forestry experts use the medium spatial resolution data from Landsat to estimate forested area in the allometric equations for estimating forest carbon(GOFC-GOLD 2007). However, area is only one of several variables required in the estimation of forest carbon (Waggoner 2009; Fagan and Defries 2009). Additional data are required from field studies and other types of remote-sensing instruments—particularly radar and lidar to obtain forest structure and biomass, both of which are additional required variables for the allometric equations. The parcel size and location of interest can also determine the choice of instrument. For instance, in estimating forest carbon for a small number of hectares for U.S. landowners, lidar has been the only instrument used in some cases (Fagan and Defries 2009; Macauley et al. 2009). Routine use of lidar is limited at present; because it is flown on aircraft, imaging costs are relatively large, and permission to access airspace is required (Fagan and Defries(2009) document these limits).

Aside from estimation of carbon, Landsat also provides a means for helping to monitor leakage, permanence, and additionality. The global coverage of Landsat could help to observe leakage, and the continuity of Landsat over time helps to assess permanence and additionality. To shed further light on the value of information for helping to alleviate these concerns, we exercise the three scenarios as a guide. They enable us to portray differences among geographic and temporal concerns.

In the case of high offsets, international forest carbon management plays a large role. In this case, we assume Landsat information has value in monitoring changes in the geographic and temporal distribution of forest carbon—that is, in monitoring leakage, permanence, and additionality. The case of no international offsets is the other extreme. Because domestic climate policy does not allow forest carbon sequestration outside of the United States in this case, the global and temporal coverage of Landsat has less value. In this case, Landsat would provide information for U.S. forest carbon management only.

To attribute value to Landsat information in a forest carbon market, then, we assume that Landsat meets some but not all of the total information required by the market. We also assume that at most, the total information required has a value in the range of previous studies of information’s value in other applications. In section 2, we cite findings by Nordhaus (1986) that this value is approximately 1 percent of the value of the relevant market. Within our assumed ceiling of 1 percent, we ascribe values to

Landsat 9 and Landsat 10. We assume a smaller value of information from Landsat 9 than from Landsat 10 because the hyperspectral imager on Landsat 10 is expected to enhance discrimination among tree species and forest health, possibly reducing the need for field observations. In addition, Landsat 10 will include a thermal imager, thus continuing to provide the same basic data as Landsat 9.

Because the value of information is a key assumption, but one for which we have only the reasoning discussed here as a basis for the assumption, we choose conservative values (shown in Table 3). They range from .02 percent to .12 percent, with larger values for both Landsat 10 and the high offsets scenario. We discuss the results of these assumptions in the next section.

Table 3. Scenarios for Attributing Information Value (percent of offset expenditures)

Program	Base case	High offsets case	No international offsets case
Landsat 9	0.05	0.08	0.02
Lansat 10	0.1	0.12	0.04

5. Results

Under our assumption of a transition from Landsat 9 to Landsat 10 during 2022–2026, we estimate the discounted net benefit of Landsat in each of the three cases. Table 4 reports the values for the median, as well as the5 and 95 percent confidence intervals. These results illustrate the value of information we ascribe to Landsat in forest carbon management under different policy scenarios, assuming a shift to new imaging technology.[8]

The largest net benefit is in the high offsets scenario, in which international offsets figure prominently according to the EIA. In this scenario, the median value is about $9 billion. The values at the 5 and 95 percent confidence intervals are $5 and $13 billion, respectively. The next-largest value is estimated for the basic scenario, with a median value of about $8 billion and values at the 5 and 95 percent confidence intervals

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[8] The results are not the net benefit of the overall Landsat program, as we used the annualized costs for only the years 2022-2026, not the full costs of investment in Landsat 9 and 10.

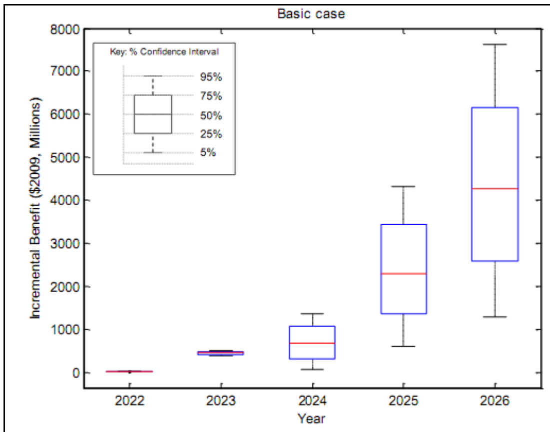
of about $4 billion and $11 billion. All estimated values of the high offsets case exceed those of the basic case, reflecting the large size of offsets expenditures in the high case. (Even though the prices of offsets are expected to be less in the high offsets case than in the basic case, the larger physical quantity of offsets used to meet the stabilization goals leads to larger expenditures.)The net benefit in the case of no international offsets is negative, with a median value of about -$3 billion. The estimated values at the 5 and 95 percent confidence intervals in this case are -$5 billion and -$0.8 billion, respectively. The result for this case reflects the much smaller amount of offsets expenditures.

Table 4. Cumulative Discounted Present Value, 2022–2026 ($2009 billions)

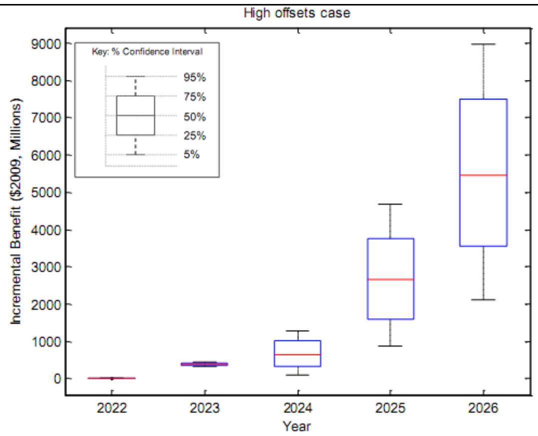
Scenario	**(5%, median, 95%)**
Basic case	(4.1,7.9,11.21)
High offsets case	(5.1,9.1,13.1)
No international offsets case	(-5.5,-2.9,-0.2)
No additional value of information for new technology	(-5.1,-1.9,1.1)
Slow adoption of new technology	(2.3,5.2,8.4)

The incremental results by year reflect changes overtime in terms of the volume and prices of offsets as well as the transition from Landsat 9 to Landsat 10. The results also include our assumed increase in the value of information with Landsat 10. From Table 2, recall that volume increases over the period, but price falls in the basic case, and volume and price both increase in the high offset case. From Figure 4, panels 1, 2, and 3, the net benefits in the basic case exceed those of the high offsets cases during 2022–2024, but a relatively larger increase takes place over time in the high offsets case (as emissions limits are met primarily through offsets). The rate of increase is largest in both cases in the 2024–2025 period. In 2024, the net benefits are positive in the case of no international offsets but become negative by 2026.The range of uncertainty also grows overtime in all cases, consistent with how we have modeled the uncertainty parameter.

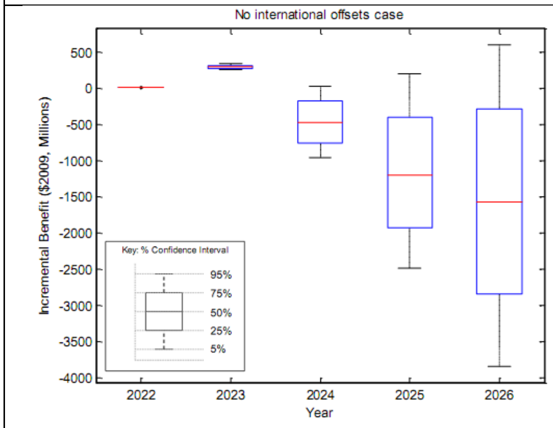
Figure 4. Estimated Benefits by Year



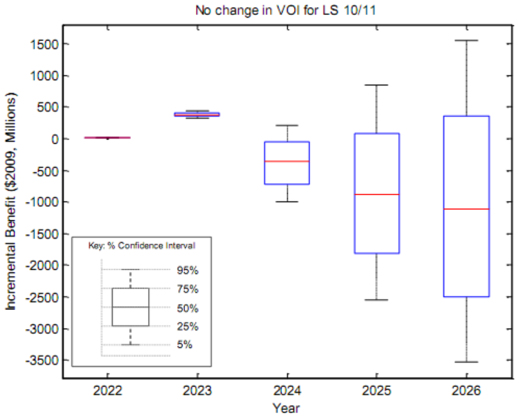
1. Basic case



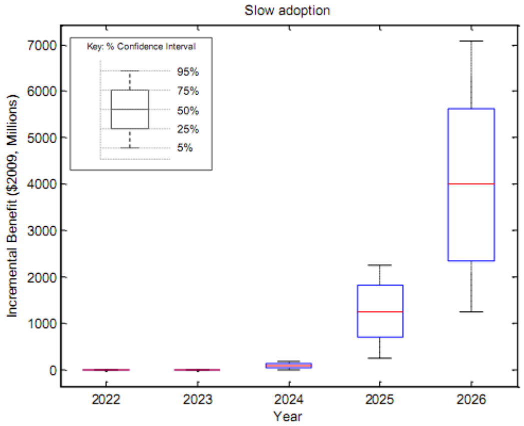
2. High offsets case



3. No international offsets case



4. No change in value of information for Landsat 10



5. Slow adoption

One key parameter for these results is the assumed values of information for Landsat 9 and Landsat 10 based on Nordhaus (1986).We may be understating the value of information for many reasons. For example, Landsat could become increasingly relied on for benchmarking the permanence, additionality, and leakage concerns associated with forest carbon sequestration, as previously noted. Or, we may be overstating the value of information from Landsat if, for example, LIDAR and other sensing technologies become more relied on than Landsat 9 or the proposed hyperspectral imager for Landsat 10 in measuring forest carbon, also as discussed earlier. We also may be overstating the value of Landsat for measuring domestic forest offsets to the extent that permanence, leakage, additionality, and other dimensions of forest management in the United States are monitored using means other than, or in addition to, Landsat. In this situation, the negative values in the case of no international offsets could be even larger (more negative).

Our model allows us to vary these assumptions. To illustrate, we consider two examples in which we vary assumptions about the adoption rate of Landsat 10 and the value of information. We use the basic case. The results are in panels 4 and 5 of Figure 4. A slower adoption rate reduces estimated median net benefits by about a third. No increase in the relative value of information for Landsat 10 results in negative net benefits (although the estimate at the 95 percent confidence interval is positive).

The results show the sensitivity of the value of Landsat data and instrument choice to the public policy context. The findings also rest on several key assumptions. One is our starting point of previous value-of-information studies, which finds the value to be about 1 percent of the value of the related market. Another assumption is the allocation of a portion of this percentage to the subset of information represented by Landsat legacy and new instruments.

6. Summary and Conclusions

We developed a quality-adjusted expenditure framework for combining new instrument choice with a value-of-information approach to characterize public investment in the nation’s Landsat system. The framework allows identification of the value of Landsat data in economic decisions. Our ultimate aim is to help inform new instrument investment choices. Legacy instruments offer “data continuity.” New instruments offer new ways of seeing our world. Both types of investments have value. Not only do we seek to help inform whether investments will pay off, but we can help identify priorities for program management, other decisionmakers, and the public at large in pushing the frontier of the future generation of satellite observing systems.

We have illustrated the framework by applying it to the case of forest carbon sequestration, a key provision of leading policy proposals for managing climate. We ascribe value to Landsat data by assuming that these data inform the physical assessment of forest carbon and the monitoring of policy-related concerns about leakage, permanence, and additionality. By using an expenditure function inclusive of the full menu of policy attributes (emissions reductions as well as offsets), we are able identify the relative Landsat contribution. In other words, the value of Landsat in improving management of forest sequestration directly enhances the quality of a forest offset, informs the trade-off between an offset and an emissions reduction, and, in turn, advances the overall cost-effectiveness of climate policy.

Based on EIA policy scenarios that include international forests, the value of Landsat data related to forest offsets can be as large as $1 billion annually and several billion dollars in present value over the sample period of 2022–2026.In an EIA policy scenario that excludes international forests, however, the value of the data is less than the annualized cost of the Landsat program in the sample period. The results are particularly sensitive to assumptions about the improvement in forest carbon measurement enabled by the new hyperspectral imager.

More generally, we emphasize that our findings hinge critically on determinants of the value of information and understanding of the policy context in which the information is used. In the absence of any previous estimates of the value of Landsat data, we draw guidance from other valuation studies. We thus urge further research to characterize and estimate the value of Landsat data. The development of environmental markets for some ecosystem functions (for example, as provided in the U.S. by provisions in section 2709 of the Food, Conservation and Energy Act of 2008, and as underway in some developing countries) could offer opportunities for this line of inquiry. Another desirable research path is characterizing the economies of scope offered by Landsat data. Landsat observations inform not only forestry management but also a wide variety of other land use actions, ranging from farming to urbanization. Omitting this scope can lead to underestimates of the value of the data. Finally, the sensitivity of our results to the characteristics of new instruments suggests the usefulness of value-of-information studies that could be carried out in advance of instrument selection.

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