From Experience to Insight: Advancing Forest Management with Decision Science

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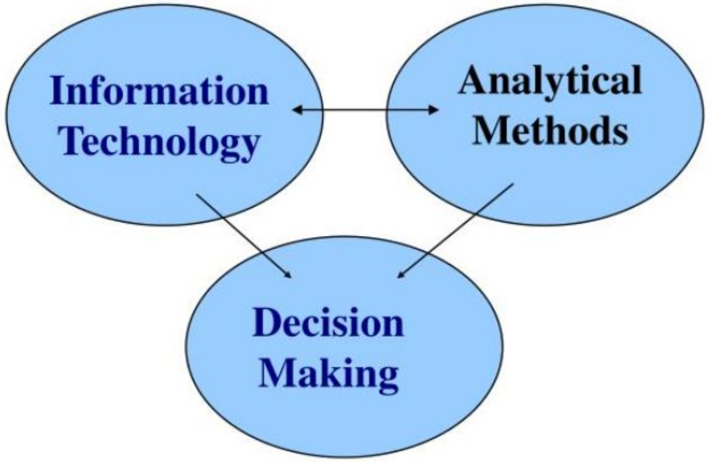
Outline

- Decision Science is more than just finding good solutions
- Example: the airline industry
- Optimizing forest management for an integrated forest products company
- Integer programming: exact solution methods vs. heuristic solution methods
- Managing forests for carbon sequestration
- Uncertainty: Forest management in a burning world
- Conclusion

Decision Science – Defining your Problem

- Insight about your management problem
- Clear, measurable objectives
  - What does “sustainability” mean for you?
- Identifying and quantifying constraints
  - Constraints vs. objectives
- Organizing your information
  - What’s important, what’s not
  - What’s missing?



Decision Science and Modeling

- How you model your problem matters
  - Computational efficiency
  - Does your model accurately represent the key aspects of your real-world problem
  - Time consistency (McQuillan (1986)[1])
    - Planning horizon
    - Ending conditions (da Silva et al. (2024)[2])

1. McQuillan, A.G. 1986. The Declining Even Flow Effect—Non Sequitur of National Forest Planning. *For. Sci.* doi.org/10.1093/forestscience/32.4.960
2. da Silva B.K., F. Rezaei, S. Tanger, J. Henderson, E. McConnel, C. Sun. 2024. Terminal value: A crucial and yet often forgotten element in timber harvest scheduling and timberland valuation. *For. Poly. Econ.* doi.org/10.1016/j.forpol.2024.103188

Exponentially Increasing Information

- Remote sensing
  - In many cases, we are now working with a complete census for our forest inventory
    - Especially in plantations
    - This is still a challenge in mixed-hardwood natural forests (but it’s just a matter of time)
- Capture data in real-time
  - Smartphones, QR-Codes
  - GPS trackers, Barcodes and RFID

Example: Airline Industry

- Think about what they do…
  - Track aircraft, passengers, their bags, aircrews, ground crews, gates, fuel supplies, food suppliers, and a host of other things
  - Many legal rules to follow
  - Dealing with people (never predictable)
  - Not kill anyone 😕

Example: Airline Industry

- The situation they face is constantly changing
  - Weather, maintenance issues, crew members who are sick, passengers who have to be re-routed
  - Having planes, crews, and other resources in the right place at the right time
  - They have to constantly adapt and respond as competently and effectively as possible
- We are upset when they fail, but when you think about it, they are incredibly organized and efficient
- And they have to be. They have people's lives literally in their hands.

Integrated Forest Products Company

- Forestland parcels
  - Area, location, inventory, site, management history, management restrictions
- Mills (demand centers)
  - Material requirements
- Harvesting and transportation
  - Road network, logging equipment and crews, logging trucks
- Nurseries
  - Quantity and type of planting stock (clones, seedlings) available when needed

Integrated Forest Products Company

- Policy environment
  - Legal & environmental constraints
- Changing markets
- New technologies
  - Remote sensing, new clones
- Managing people
  - Employees, contractors

Basic Forest Management Problem

- Identifying what/where to harvest
  - Satisfy mill requirements
  - Plan harvesting and transportation logistics
  - Satisfy environmental and legal constraints
  - Plan nursery operations to have the right seedlings available for the sites that will be harvested when they are harvested
  - For eucalyptus, choosing whether to coppice or replant (to take advantage of potentially faster growth with new clones)

Basic Forest Management Problem

- Additional issues
  - How to manage for carbon?
  - How to adapt to and plan for a changing climate?
- This is a large, complex problem, but arguably simpler than the airlines' management problems.

Basic Forest Management Problem

- This can be formulated as a large mixed-integer linear programming model
  - Many variables are 0-1, indicating you either do something at a given time, or you don’t
  - Potentially hundreds of thousands of variables

  - Of course, these are hard to solve
  - A lot of research has been done on this problem
    - Usually employing heuristic solution methods

Integer Programming: Exact Solution Methods vs. Heuristic Solution Methods

- Very large MIP models cannot, in general, be solved with exact methods
  - So, we *have* to use heuristics, right?
  - But are they mutually exclusive? Do we have to choose one or the other?

    - Not at all!

$$Max \;\; Z = \sum_{m=1}^{M} \sum_{t=1}^{3} c_{mt} \cdot A_m \cdot X_{mt} \qquad (1)$$

Subject to

$$\sum_{t=0}^{T} X_{mt} \le 1 \qquad \text{for } m = 1, 2, \dots, M \qquad (2)$$

$$\sum_{m=1}^{M} v_{mt} \cdot A_m \cdot X_{mt} - H_t = 0 \qquad \text{for } t = 1, 2, \text{ and } 3 \qquad (3)$$

$$H_t - H_{t+1} \le 0 \qquad \text{for } t = 1 \text{ and } 2 \qquad (4)$$

$$-1.2 H_t + H_{t+1} \le 0 \qquad \text{for } t = 1 \text{ and } 2 \qquad (5)$$

$$\sum_{m=1}^{M} \sum_{t=0}^{3} (Age_{mt}^{60} - 40) A_m \cdot X_{mt} \ge 0 \qquad (6)$$

$$\sum_{i \in C_j} X_{it} \le 1 \qquad \text{for all } C_j \text{ and } t = 1, 2, \text{ and } 3 \qquad (7)$$

$$X_{mt} \in \{0, 1\} \quad \text{for } m = 1, 2, \dots, M \text{ and } t = 0, 1, 2, \text{ and } 3 \qquad (8)$$

Vs

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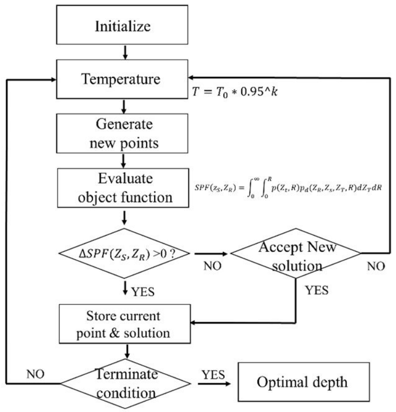
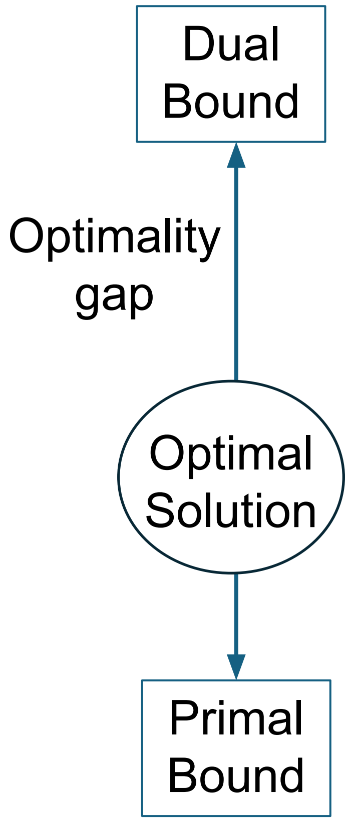
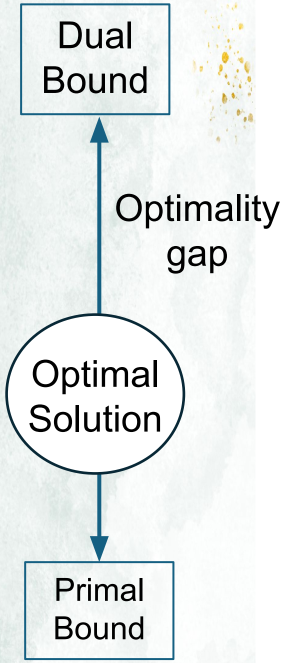


How Exact Methods Work: Branch and Bound

- You solve a "relaxed" version of model
  - Ignore integer constraints – > Gives you a linear programming problem that is "easy" to solve
  - This gives you a "dual bound" on the solution
- You start branching by "fixing" some non-integer variables as integers
  - When you "fix" a variable, the objective function value goes down
  - Eventually you get a feasible solution (all integer constraints satisfied), so you have a "primal bound"
- The difference between the primal bound and the dual bound is called the "optimality gap"



Integer Programming: Exact Solution Methods vs. Heuristic Solution Methods



- One problem with heuristic solutions is you don't know how good your solution is.
- Embedding heuristics within a branch and bound algorithm gives you a metric for how good your best feasible solution is.
- Another advantage of exact methods is that you (sometimes) get shadow prices from the relaxed LP solutions.
- Again, the point of modeling is not just to obtain a good solution. It's about gaining insight.

The Value of Shadow Prices

- They provide insight about the problem
- Shadow prices can also be used in solving the problem
  - Solution methods based on estimating shadow prices have not been adequately explored in the forest management literature
    - Hoganson and Rose (1984)[1]
    - Lagrangean decomposition
    - Column (variable) generation (and reduction)

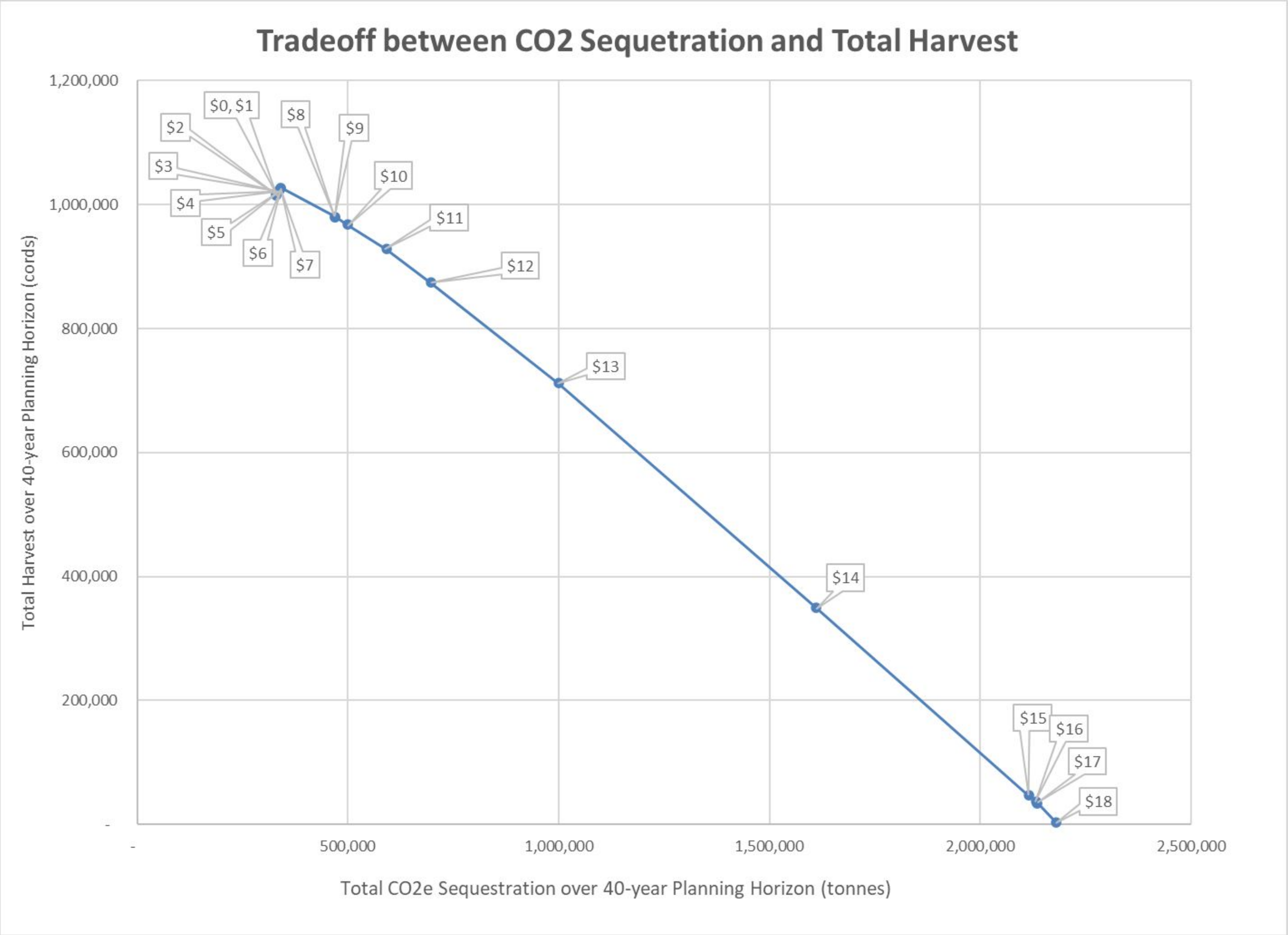
1. Hoganson, HM, and DW Rose. 1984. A simulation approach for optimal timber management scheduling. For. Sci. doi.org/10.1093/forestscience/30.1.220

Carbon

Modeling Carbon

- Carbon stocks (how much you have)
  - Use accounting constraints to calculate the carbon content of your forest at the beginning and/or end of each planning period
  - C_t = the carbon stock in period $t \in \{0, 1, \dots, T\}$
- Carbon accumulation (net accumulation)
  - CA_t = the C accumulation in period $t \in \{1, \dots, T\}$
  - $C_{HWP,t}$ = C in harvested wood products
  - $\boxed{CA_t = C_t - C_{t-1} + C_{HWP,t}}$

Potential of Forests to Offset Em



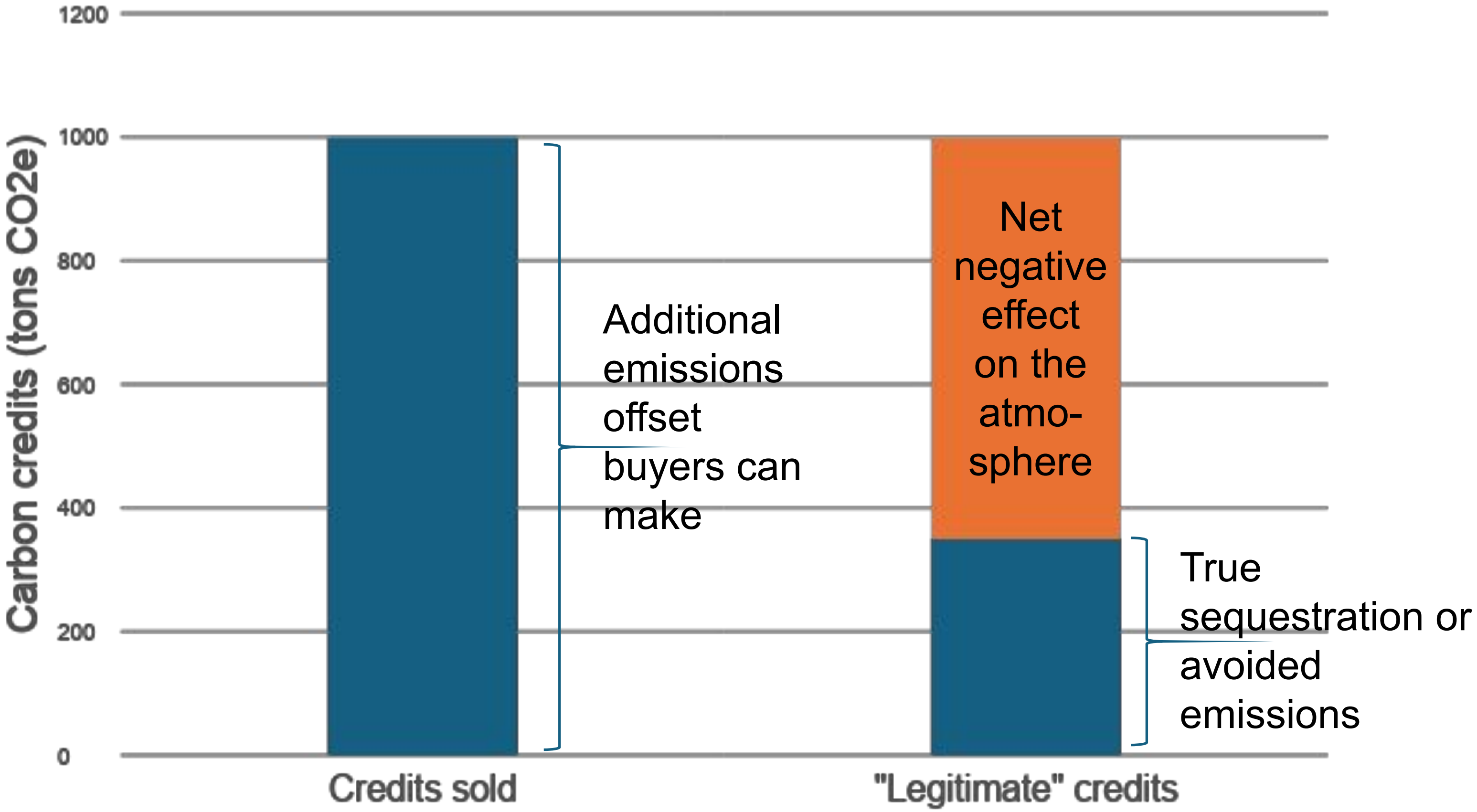
Modeling Carbon vs Carbon Credits

- Carbon stocks vs Carbon accumulation
  - Accounting for carbon stocks assumes that you get paid a "rental fee" for the carbon you store
  - Accounting for carbon accumulation assumes that you get paid for your net sequestration
- Neither approach actually works the way carbon offset markets work

Carbon - Additionality

- Additionality is the Achilles heel of carbon offset markets
  - And leakage, but let's focus on additionality
- "Additionality" means compared to what you would have done in the absence of the carbon contract
  - Additionality is impossible to measure
  - Very hard to prove the counterfactual

While counterfactuals can be useful for analysis and discussion, proving them in a definitive sense is not possible due to their speculative nature. (AI summary: proving the counterfactual.)



“Legitimate” credits here means they are truly permanent, additional, and not cancelled out by leakage.

Uncertainty

- Uncertainty is the truly big challenge in operations research

Uncertainty

- Perhaps the ultimate problem in forest management that involves uncertainty is fire management

Four Fire Management Problems

- Pre-suppression
  - Designing landscapes to minimize expected loss from fire
  - Staging equipment and crews
- Suppression
  - Allocating resources to multiple fires
  - Optimizing the suppression of an existing fire

Designing Landscapes to Minimize Expected Net Loss from Fire

- First understand and model how fire starts and spreads on the landscape
- Generate a map of the probability of burning
  - Boundary issues
  - The probability of a given cell burning depends on the probability of adjacent cells burning
  - This is what makes this a particularly intractable problem
- Multiply the probability of burning map with the cell value map to get the expected loss from fire
- Apply treatments to the landscape and re-compute the probability of burning map and the expected loss from fire

Designing Landscapes to Minimize Expected Net Loss from Fire

- No time dimension: what is optimal in period 2 depends on what happens in period 1.
  - You can assume nothing burns, but if anything burns, then that changes everything.
- Keys to finding better solutions:
  - Find more computationally tractable ways to estimate the burn probability map.
  - Find better ways to select treatment scenarios to evaluate.

Conclusions

- Decision science is about more than obtaining good solutions – it's about insight
- There is still a lot of room for improvement in forest management modeling
  - What can we learn from other industries?
  - Don't forget about exact solution methods
    - Probably not possible for landscape design with fire
- Carbon is important, and forests can contribute
  - But make sure you make a net positive contribution
- Uncertainty is a major challenge
  - No analog to fire management (?)

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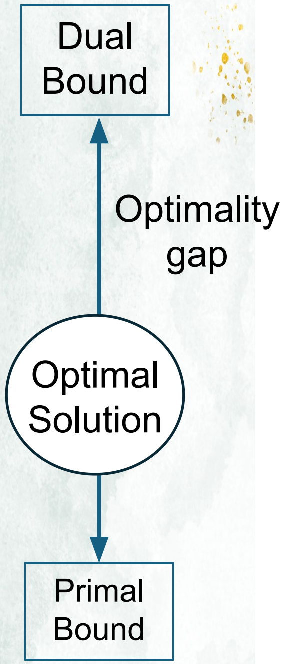
Muito Obrigado!

Basic Forest Management Problem

- How to solve this problem?
- Learn from other industries
- Work with universities
- Multi-dimensional, interdisciplinary problem
  - Data management specialists
  - Biometricians/remote sensing/forest inventory specialists
  - Management science/decision science/operations research specialists
  - Forest economists

How Exact Methods Work: Branch and Bound

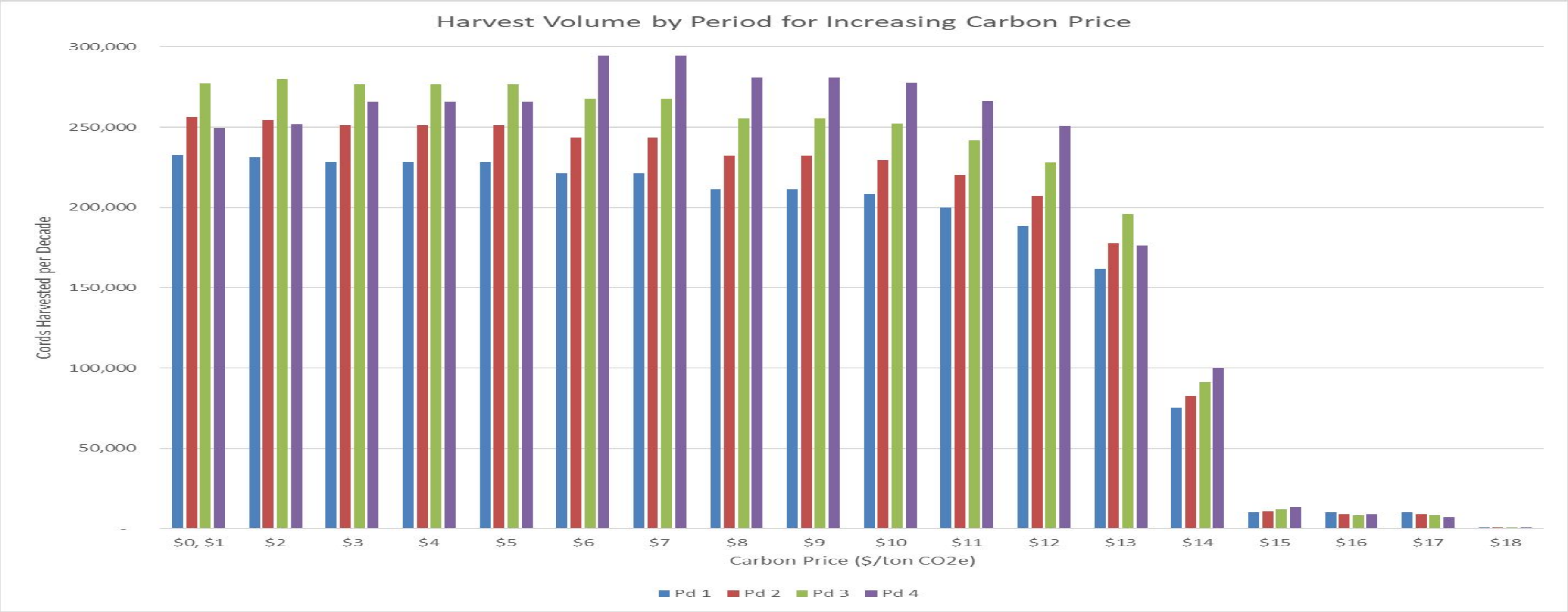


- The rest of the algorithm works on narrowing the optimality gap by either lowering the dual bound or increasing the primal bound
  - You have completely solved the problem when the gap = 0
- Good heuristic methods increase the primal bound by finding better feasible solutions
- Smart “branching” strategies lower the dual bound by fixing mutually-exclusive sets of variables, with one option on one branch and the alternative on the other
- “Cuts” are constraints that can be added to the model to tighten the “relaxed” model

Potential of Forests to Offset Emissions

- Managing US forests primarily for carbon could offset up to 12% of annual 2020 US GHG emissions.[1,2]
- Mostly reforestation (5.9%) and improved natural forest management (5.1%)
- Also avoided conversion (0.7%) and improved plantations (0.2%)
- Falls to 10% at $100/ton CO_2e and 2% at $10/ton CO_2e

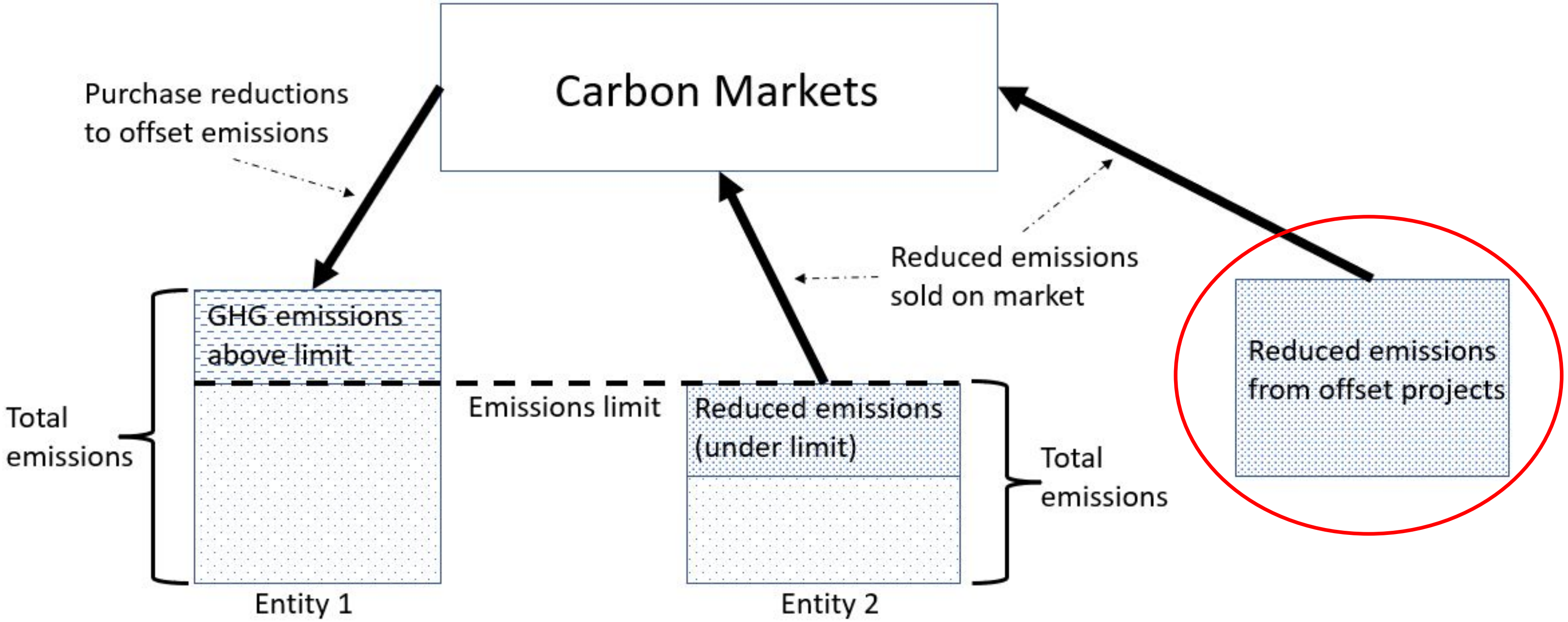
1. Fargione et al. 2018. Natural climate solutions for the United States. Sci. Adv. 2018; 4:eaat1869
2. US EPA. 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks (5,222 /ton CO_2e)


Harvest Volume by Period for Increasing Carbon Price
Cords Harvested per Decade
300,000
250,000
200,000
150,000
100,000
50,000
-
$0, $1
$2
$3
$4
$5
$6
$7
$8
$9
$10
$11
$12
$13
$14
$15
$16
$17
$18
Carbon Price ($/ton CO2e)
Pd 1
Pd 2
Pd 3
Pd 4


Net Sequestration by Period for Increasing Carbon Price
Carbon Sequestration per Decade (tons CO2e/decade)
700,000
600,000
500,000
400,000
300,000
200,000
100,000
-
Carbon Price ($/ton CO2e)
Pd 1
Pd 2
Pd 3
Pd 4

Carbon Offsets in Regulatory Markets

CA, RGGI(CT, DE, ME, ME, MD, MA, NH, NJ, NY, RI, VT, VA), WA, OR



Key point is that offsets purchased by Entity 1 allow the entity to emit more GHG than their regulatory limit.

Exponentially Increasing Information

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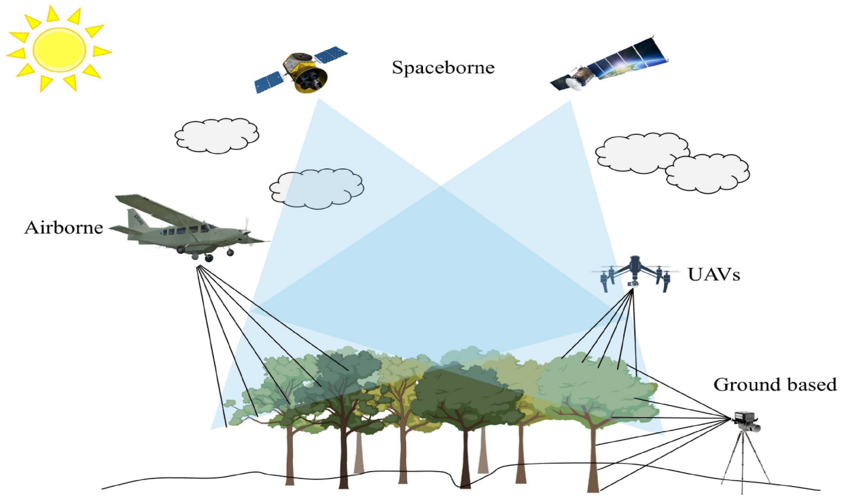
  - In many cases, we are now working with a complete census for our forest inventory
    - Especially in plantations
    - This is still a challenge in mixed-hardwood natural forests (but it's just a matter of time)



Example: Airline Industry

- Modern airlines must have sophisticated data management systems and use sophisticated models to keep everything running as smoothly as possible.
- Is the forest products industry as efficient as the airline industry?
- If not, what can we learn from them?