Appendix 1:
Methods, Assumptions, and Key Results of Selected Carbon Sequestration Studies

Parks and Hardie (1995)

Empirical framework: Optimization model that differentiates U.S. farm lands by expected net returns to agriculture, expected net returns to forestry, and potential to sequester carbon in trees. Develops supply curves for carbon sequestration on U.S. agricultural lands by exhausting a fixed budget to subsidize land-use change to forest under various sequestration program designs.

Geographic scope:	116.1 million acres of privately owned U.S. cropland and pasture classified as non-prime farmland and suited to forest. Land is disaggregated into 433 regions with each region linked to a forest type and thus a potential to sequester carbon.
Baseline time period:	A composite year reflecting the period 1985-90.
Land base:	Private agricultural land classified as not irrigated and not prime farmland.
Activities analyzed:	Shifting marginal cropland and pasture to forest.
Incentives analyzed:	Derives carbon prices by exhausting fixed sequestration budget.

Program design and incentive structure:

- Afforestation program modeled after CRP. All land enrolled in year 1 for 10 years, after which the program ends. Program provides 50 percent of tree-establishment costs paid in year 1 and annual rental payments equal to forgone agricultural rents.
- Pays for carbon in trees only.
- Scenarios analyzed:

  S1: eligible land—cropland and pasture/objective—minimize cost per acre,
  S2: eligible land—cropland and pasture/objective—minimize cost per ton of carbon,
  S3 and S4—objectives similar to S1 and S2 but limited to cropland.

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Treatment of time—static. Model features a one-time decision to afforest lands without considering the implications of potential future harvest.
- Permanence—not explicitly considered. After 10 years, forestry is assumed to be the land use with the highest expected return (so annual payments are not needed to keep land in trees).
- C-stock equilibrium (CSE)—not explicitly considered. Afforestation program ends before CSE occurs.

Key results:

- For a program with a present value of $4.60 billion and targeting both cropland and pasture:

  S1: Over 10-year program period, enrollment is 23.1 million acres, carbon sequestration is 40.8 MMT per year, average discounted costs = $112.54 per mt.
  S2: Over 10-year program period, enrollment is 22.2 million acres, carbon sequestration is 44.1 MMT per year, average discounted costs = $104.20 per mt.

- For scenario S2, the marginal cost (MC) of sequestration rises slowly from 0 to 100 mt per year then increases sharply.
- Enrollment and sequestration levels decrease more than 50 percent and costs more than double when only cropland is targeted.

Alig et al. (1999)

Empirical framework: Optimization model linking U.S. agriculture and forestry sectors through competition for privately owned land. Agriculture modeled using ASM (see McCarl and Schneider). Forestry sector has nine geographic regions, six product classes, two private land ownership classes, four forest types reflecting species composition, three site productivity classes, four management intensity classes, and six classes reflecting land's ability to shift between sectors. Model is simulated in 10-year time steps, with ASM solved statically at each step.

Geographic coverage: Contiguous 48 States.

Baseline period: U.S. agricultural and forest sectors initially calibrated to 1990 conditions. Model is then simulated in 10-year time steps through 2079, with no afforestation incentives to set the baseline. Policy results are tracked through 2039.

Land base: All agricultural and forest land in the contiguous 48 U.S. States.

Activities analyzed: Shifting land between agriculture and forestry.

Incentives analyzed: Sets payments to afforest agricultural lands at levels needed to achieve exogenously specified afforestation levels.

Program design and incentive structure:

- Programs start in 1990 and runs through 2079.
- Carbon-sequestration program modeled as subsidy for afforestation.
- Pays for incremental ecosystem carbon (carbon in trees, woody debris, understory, floor, and soil). Trees can be harvested with no deforestation penalty.
- Scenarios:
  S1: Force 12.1 million acres of agricultural land to shift to forest in decade 1 (1990-99).
  S2: Constant carbon flux of 1.61 gigatons per decade.
  S3: Flux set 0.4 gigatons above baseline in each decade.
  S4: Flux starts at baseline level and increases 0.2 gigatons above baseline in each succeeding decade.

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Afforestation and forest management decisions affect sequestered carbon levels.
- Framework accounts for interactions between the agricultural and forestry sectors.
- Management of public forests specified exogenously and held fixed.
- Existing farm programs assumed to end after 1 decade.
- Treatment of time: Dynamic, using 10-year time steps and 4-percent discount rate.
- Permanence: Reflected in carbon accounting but not in pricing of sequestration incentives.
- CSE: Forests generally harvested before CSE occurs.

Key results:

- Policies to afforest agricultural lands will generate offsetting deforestation activities in the forest sector. Over time, many lands will move back and forth between agriculture and forestry.
- Across the three carbon flux scenarios (S2-S4)
  Net transfers of land from agriculture to forest, relative to the baseline, range between 8.4 million acres and 21.4 million acres over the period 1990-2039.
  Over the 90-year simulation, in terms of the net present value:
    Society welfare decreases between $22.7 billion and $55.8 billion,
    Domestic agricultural producers gain between $13.5 billion and $44.3 billion,
    Domestic agricultural consumers lose between $34.4 billion and $83.9 billion,
    Domestic forest producers and consumers gain and lose depending on the scenario.

Stavins (1999)

Empirical framework: Econometric model describing the shares of county land in forest and in agriculture. Explanatory variables include agricultural rents, farm production costs, existing forest area, tree-establishment costs, conversion to cropland costs, and net returns for a one-time forest harvest. Simulates afforestation programs by exogenously increasing forest rents and deforestation costs. Uses changes in forest area and age to estimate changes in carbon sequestered. Estimates regional marginal cost curve for sequestered carbon by subtracting baseline sequestration from sequestration at different levels of an afforestation subsidy/deforestation tax.

Geographic scope:	Delta States (Louisiana, Arkansas, and Mississippi).
Baseline period:	Model estimated with panel data for 36 counties/parishes covering period 1935-84. Baseline scenario derived by simulating the model over 90-year period with the afforestation payment/deforestation tax set equal to zero.
Land base:	Agricultural and forest land
Activities analyzed:	Shifting agricultural land into forest.
Incentives analyzed:	Exogenously specifies a range of afforestation payments/deforestation penalties.

Program design and incentive structure

- Carbon-sequestration program modeled as subsidy for afforestation and a tax for deforestation.
- Pays for ecosystem carbon (carbon in trees, woody debris, understory, floor, and soil).
- Model simulations run for 90 years.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected longrun return to land.
- Framework accounts for factors that may make landowners require a premium to shift land to forest.
- Sequestered carbon given in present value terms to account for the time profile of sequestration.
- Treatment of time: Dynamic using annual time step and 5-percent discount rate.
- Permanence: Explicitly accounted for—agents paid when they afforest and penalized when they deforest.
- CSE: Not an issue. Trees can be harvested at any time (and generally are harvested before reaching CSE).

Key results:

- For Delta States, MC of sequestering carbon rises gradually and linearly to 6.4 million mt per year. At that level: MC = $79.86 per mt, net afforestation is 4.6 million acres, carbon tax/subsidy = $109.87 per acre.
- Above 6.4 million mt, MC of carbon sequestration increases steeply becoming nearly asymptotic at about 14.5 million mt.
- For low levels of net GHG emission reduction, sequestration costs are similar to abatement cost.

Plantinga et al. (1999)

Empirical framework: Econometric land-use model describing the shares of county land in forest, agriculture, and other uses. Key explanatory variables include agricultural and forest rents, population density, and two measures of land quality. Simulates afforestation programs by exogenously increasing forest rents. Uses changes in forest area to estimate changes in carbon sequestered.

Geographic scope:	Models estimated for Maine (ME), South Carolina (SC), and Wisconsin (WI).
Baseline time period:	Data cover period 1971-96. Baseline scenario derived by simulating the model over 60-year period with afforestation payments set equal to zero.
Land base:	Private agricultural and forest land in ME, SC, and southern two-thirds of WI.
Activities analyzed:	Shifting agricultural land into forest.
Incentives analyzed:	Exogenously specifies a range of afforestation payments.

Program design and incentive structure:

- Afforestation program modeled after CRP.
- Starts in 2000 and runs for 60 years in 10-year steps.
- Landowners decide to enroll, leave program, or reenroll at the start of each decade.
- Provides annual fixed payment and one-time tree establishment costs paid in year of enrollment. No penalty for deforestation.
- In each State, enrollment capped at 25 percent of its agricultural land.
- Scenarios analyzed:
  S1—Constant 1995 population, uniform payments, harvests allowed.
  S2—Constant 1995 population, uniform payments, harvests not allowed.
  S3—Increasing population, variable payments, harvests not allowed.
  S4—Increasing population, uniform payments, harvests allowed.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected longrun return to land.
- Framework accounts for factors that may make landowners require a premium to shift land to forest.
- Without afforestation, net sequestration on agricultural lands is zero.
- Land in urban/other uses held fixed implying only agricultural land shifts to forest.
- Sequestered carbon given in present value terms to account for the time profile of sequestration.
- Treatment of time: Dynamic in 10-year time steps and 5-percent discount rate.
- Permanence: Not accounted for—agents are paid to afforest but are not penalized for deforesting.
- CSE: Not an issue. Forests in ME, SC, and WI do not reach CSE in 60 years.

Key results:

- Across scenarios, the MC of carbon sequestration rises (almost) linearly from the origin. At 25 percent enrollment cap, the MC of sequestration varies:
  From $107.10 to $135.28 per mt in ME (sequestration = 3.176 million mt),
  From $50.73 to $101.46 per mt in SC (sequestration = 14.518 million mt),
  From $84.55 to $107.10 per mt in WI (sequestration = 54.444 million mt).
- S1 is almost always least-cost scenario.
- Lake States and Midwest are the most cost-effective areas to afforest; the Northeast is the least cost effective.

Antle et al. (2001)

Empirical framework: Field-level econometric production models for winter wheat, spring wheat, and barley in continuous cropping and crop-fallow rotations and permanent grass. Incorporates these models into a simulation model that sets farmer decisions on land allocation and input use in response to exogenous policy shocks. A crop ecosystem model (Century) then determines the net effect on soil carbon.

Geographic scope: Eastern Montana's dryland grain-producing region.

Baseline time period: Data are from mid-1990s. Baseline scenario derived by simulating the model over 20-year period with sequestration payments set equal to zero.

Land base: Privately owned cropland and pasture.

Activities analyzed: Switching cropland to permanent grasses.
Switch from crop-fallow rotations or permanent grass to continuous cropping.

Incentives Analyzed: $2.07 to 20.71 per acre to adopt continuous cropping.
$5.18 to $51.77 per acre to shift land to permanent grasses.

Program design and incentive structure:

- Provide payments to farmers to adopt continuous cropping and shift land to permanent grass (activities are analyzed separately).
- Payments for shifting land to grasses are in addition to CRP payments.
- Simulations begin today and run for 20 years.
- Scenarios analyzed (and discussed):
  PG: switch land to permanent grasses—all cropland and pasture is eligible,
  CC: shift to continuous cropping—only lands in crop fallow rotations and grasses are eligible.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected returns to each field.
- Use of site-level data (i.e., field and farm) accounts for the spatial heterogeneity in biophysical and economic characteristics across farms.
- Permanence: Not accounted for.
- CSE: Not accounted for. Program ends before reaching CSE.
- Treatment of time: Static.

Key results:

- Spatial heterogeneity with respect to biophysical and economic characteristics is an important consideration in the design of farm policies to sequester carbon. Across locations in the study area, the MC of sequestering carbon ranges from $51.15 to $511.51 per mt in the PG scenario and from $12.28 to $143.22 per mt in the CC scenario. In the CC scenario, the average cost of sequestering carbon was less than $51.15 per mt in all regions.
- From the taxpayer viewpoint, a policy to promote CC is relatively more efficient at sequestering soil carbon than a PG policy. Over 20 years, the PG policy that pays farmers $51.77 per acre per year sequesters 7 MMT of carbon at an undiscounted Government cost of $3.15 billion. Over 20 years, the CC policy pays farmers $4.14 per acre per year to sequester 7.61 MMT at a Government cost of $206.34 million.
- Over the range of payments considered, soil carbon sequestration ranges from 2.37 to 6.76 MMT under the PG scenario and from 7.61 to 18.25 MMT under the CC policy.
- For CC policy, payments above $20.71 per acre do not significantly increase carbon sequestration because over 90 percent of land in crop-fallow rotations has been converted to CC.

Pautsch et al. (2001)

Empirical framework: Estimates an econometric model where the probability of adopting no-till is a function of net returns to conventional tillage, local soil characteristics, and regional temperature and precipitation variables. Production possibilities include 14 rotations consisting of mixes of corn, soybeans, wheat, sorghum, and hay. Econometric model is linked with a biophysical model so that changes in tillage practices can be paired with changes in soil carbon.

Geographic scope:	Iowa.
Baseline time period:	Model reflects a “typical” year during the 1990s.
Land base:	All cropland.
Activities analyzed:	Adopting conservation tillage (CC)—assumed to be no-till.
Incentives analyzed:	Specifies various levels of carbon sequestration and computes the average costs per ton needed to achieve those levels.

Program design and incentive structure:

- Provide payments to farmers to adopt conservation tillage (assumed to be no-till).
- Scenarios considered:
  S1: new CC adopters only with uniform per acre payment.
  S2: all CC adopters with uniform per acre payment.
  S3: new CC adopters with price discriminating per acre payment based on carbon-sequestration potential.
  S4: all CC adopters with price discriminating per acre payment based on carbon-sequestration potential.

Assumptions, modeling issues, and special features:

- Landowners maximize the expected returns to land.
- Use of site-level data (i.e., field and farm) accounts for the spatial heterogeneity in biophysical and economic characteristics across farms.
- Framework addresses the issue of designing programs to pay all adopters of conservation tillage versus only paying those who adopt as a result of the incentives.
- Treatment of time: Static—looks at an average year of an unspecified multiyear program.
- Permanence: Not accounted for.
- CSE: Not accounted for. Implicitly assumes carbon will accumulate as long as the program runs.

Key results:

- At a sequestration level of 1 MMT per year, the average cost per mt sequestered is about $294 in S1, $1,089 in S2, $207 in S3, and $686 in S4.
    - Regardless of payment design, the average cost per mt sequestered falls when only new adopters are targeted.
    - Regardless of who is targeted, the average cost per mt sequestered falls with a price-discriminating payment.

McCarl and Schneider (2001)

Empirical framework: The ASMGHG model—a market and spatial equilibrium mathematical programming model. Model depicts production and consumption in 63 U.S. regions for 22 traditional crop commodities, 3 biofuel crops, 29 livestock commodities, and more than 60 processed agricultural products. Trade is modeled for 28 international regions. In responding to relative changes in input prices, farmers can adjust tillage, fertilization, irrigation, manure treatment, and feed mixes. Changes in carbon sequestration associated with changes in crop-management activities are calculated using the biophysical model EPIC (Environmental Policy Integrated Climate model). Land shifting from agriculture to forestry and the associated carbon sequestration are obtained from 30-year simulations of FASOM (see Alig et al., 1999). Changes in emissions associated with livestock management based on EPA data.

Geographic scope:	Contiguous 48 States.
Baseline time period:	ASMGHG run with carbon valued at $0.00 per mt.
Land base:	All agricultural land (cropland and pasture).
Activities analyzed:	Afforestation and forest management, biofuel production, crop mix changes, changes in tillage practices, reductions in fertilizer use, reductions in rice acres, grassland conversions, changes in irrigation practices, changes in livestock management, and changes in manure management.
Incentives analyzed:	Exogenously specifies range of carbon prices.

Program design and incentive structure:

- Farmers paid for changes in land use and production practices that sequester carbon, increase biofuel production, or reduce GHG emissions. Farmers taxed for changes in land use or production practices that increase GHG emissions.
- Scenarios considered: ASMGHG simulated with carbon valued at $9.60, $48.10, $96.20, and $480.80 per mt (or $10, $50, $100, and $500 per mt in 2000 dollars).

Assumptions, modeling issues, and special features:

- Land allocated to the use with the highest expected net return.
- Simulations reflect points of market equilibrium. Simulations do not account for adjustment paths.
- Treatment of time: Static—economic agents and markets adjust fully and instantly to incentives for sequestering carbon, reducing CH_4 and N_2O emissions, and producing biofuels.
- Permanence: Not explicitly accounted for. Payments for carbon sequestration activities implicitly assume carbon is stored permanently.
- CSE: Not explicitly accounted for.
- Leakage: Explicitly accounted for (see empirical framework above and Alig et al, 1999).

Key results:

- For carbon valued at $9.60, $48.10, $96.20, and $480.80 per mt:
  Carbon sequestration is 51.80, 146.40, 238.50, and 395.50 MMT of carbon, respectively.
  Total mitigation is 53.90, 154.10, 255.70, and 425.90 MMTCE, respectively.
  Gross farm welfare increases $0.4 billion, $4.3 billion, $13.4 billion, and $76.9 billion, respectively.
  U.S. consumer welfare decreases $0.4 billion, $5.2 billion, $18.5 billion, and $104.6 billion, respectively.
- At low carbon prices, soil carbon sequestration, afforestation, and CH_4/N_2O emissions reductions activities dominate a national GHG-mitigation strategy.
- At high carbon prices, afforestation and biofuel production dominate a national GHG-mitigation strategy.
- The total contribution of CH_4 and N_2O emissions reductions activities is relatively small.

Parks and Hardie use acres, short tons, and 1987 dollars; Alig et al. use hectares, metric tons, and 1990 dollars; Stavins uses acres, short tons, and 1990 dollars; Plantinga et al. use acres, short tons, and 1995 dollars; Antle et al. use hectares, metric tons, and 1995 dollars; Pautsch et al. use acres, metric tons, and 1992 dollars; and McCarl and Schneider use acres, metric tons, and 2000 dollars. All reported monetary values have been converted to 1997 dollars, all area measures have been converted to acres, and all GHG emission reduction/carbon sequestration quantities have been converted to metric tons of carbon.