Journal of Biogeography (1995) **22**, 743–751

Potential carbon benefits of the Conservation Reserve Program in the United States

JERRY R. BARKER, GREG A. BAUMGARDNER, DAVID P. TURNER and JEFFREY J. LEE* *ManTech Environmental Research Services Corp. and *U.S. Environmental Protection Agency; Environmental Research Laboratory, 200 S.W. 35th Street, Corvallis, Oregon 97333, U.S.A.*

Abstract. Three scenarios of the Conservation Reserve Program (CRP) were simulated to project carbon (C) pools and fluxes of associated grassland and forestland for the years 1986–2035; and to evaluate the potential to offset greenhouse gas emissions through C sequestration. The approach was to link land-area enrolments with grassland and forestland C densities to simulate C pools and fluxes over 50 years. The CRP began in 1986 and by 1996 consisted of 16.2×10^6 ha cropland converted to 14.7×10^6 ha grassland and of 1.5×10^6 ha forestland. The CRP1 simulated the likely outcome of the CRP as contracts expire in 1996 with the anticipated return of 8.7×10^6 ha grassland and of 0.4×10^6 ha forestland to crop production. The CRP2 assumed that the CRP continues with no land returning to crop production. The CRP3 was an expansion of the CRP2 to include afforestation of 4×10^6 ha new land. Average net annual C gains for the years 1996–2005 were <1, 12, and 16 TgC yr^{-1} for CRP1, CRP2, and CRP3, respectively. Afforestation of marginal cropland as simulated under CRP3 could provide approximately 15% of the C offset needed to attain the Climate Change Action Plan of reducing greenhouse gas emissions to their 1990 level by the year 2000 within the United States.

Key words. Conservation Reserve Program, carbon benefit, forestland, grassland, cropland, land-cover change, Climate Change Action Plan.

INTRODUCTION

The Climate Change Action Plan (CCAP) commits the United States to reducing greenhouse gas (GHG) emissions to their 1990 levels by the year 2000 (Clinton & Gore, 1993). This means implementing a combination of reduced GHG emissions and increased carbon (C) sinks amounting to approximately 7% of the 1990 rate, or 106 TgC equivalent (CE) for all GHG emissions combined. Government supported programs such as the Conservation Reserve Program (CRP) are options for achieving the 7% reduction through C sequestration.

Management of forests to sequester and conserve C may be one way to mitigate the buildup of atmospheric CO_2 and achieve the CCAP goal (Sampson, 1993; Barker *et al.*, 1995). Forest vegetation is particularly important in consideration of C sequestration and conservation because of the large accumulation of woody biomass in living trees and woody debris through time (Simpson & Botkin, 1992). Globally, forest ecosystems contain about 60% of the terrestrial C pool and account for a large proportion of the C annually cycled through the terrestrial biosphere via photosynthesis and respiration.

Forests in the United States were probably a small C source during the early to mid-1800s as a result of tree harvesting to clear land for agriculture, wood products, and fuelwood (Heath & Birdsey, 1993; Heath *et al.*, 1993). Carbon flux into the atmosphere increased greatly through the mid-1900s as the rate of harvesting increased and many large forest fires burnt uncontrolled. Currently, U.S. forests are probably a small C sink resulting from natural forest regeneration on abandoned agricultural land, fire suppression, and the switch from fuelwood to fossil fuels. Recent modelling efforts predict that U.S. forests will probably continue to be a sink for the next 50 years with the rate of C sequestration decreasing as harvest levels rise to meet the increasing demand for wood products (Heath *et al.*, 1993; Turner *et al.*, 1993, 1995b). However, Heath *et al.* (1993) estimate that approximately 100×10^6 ha of technically marginal land throughout the United States could be afforested to maintain or even increase atmospheric C sequestration levels. Consequently, the CRP was examined (1) to project net C sequestration of associated grassland and forestland for the years 1986–2035; and (2) to evaluate the potential for the CRP to offset GHG emissions in the United States through C sequestration.

METHODS

The CRP was initiated in 1985 by the U.S. Department of Agriculture (USDA) to reduce soil erosion, maintain water quality and improve wildlife habitat on highly erodible and environmentally sensitive cropland (Osborn, 1993; Cubbage, 1992). Nearly 60% of CRP lands were in the Great Plains with the remaining located throughout the United States.

Carbon pools and flux

Carbon storage in grassland and forestland is different because of differences in plant growth strategies. Forests promote long-term C storage in trees, woody debris, forest floor, and soil (Simpson & Botkin, 1992). On the other hand, the dominant C pool in grassland is soil because of insignificant accumulation of plant debris from herbaceous vegetation (Ojima *et al.*, 1993).

Our approach to quantifying C dynamics of the CRP was to link an inventory, based on land area enrolled, with stand-level C budgets for forestland or plot-level soil C budgets for grassland. The amount of C in a specific pool was calculated by multiplying C density with land area. The modelling approach used was similar to that developed by Turner *et al.* (1993; 1995a; 1995b) to evaluate the dynamics of C in U.S. forests.

On forestland, stand level C budgets estimated C densities for tree, woody debris, understorey vegetation, forest floor and soil C pools by stand age. The stand-level C budgets were based on growth and yield tables that were obtained from the Aggregate Timberland Assessment System (ATLAS), a national-level timber inventory model developed by the USDA, Forest Service (FS) as part of the 1989 Resources Protection Act Assessment (Haynes, 1990; Mills & Kincaid, 1992). The growth and yield tables contain only growing stock volume (merchantable logs); therefore, adjustment factors were applied to account for non-commercial species (Thompson, 1989). This volume was then converted to bole C based on the relative proportion of hardwood and softwood using conversion factors presented by Turner *et al.* (1993, 1995a). Equations of allometric relationships (Cost *et al.*, 1990; Harmon, 1993) were applied to convert bole C to whole tree C and the contributions of roots, stumps, branches, tops, and cull trees. The contribution of saplings to the tree C pool was estimated based on biomass statistics presented by Cost *et al.* (1990).

The understorey-vegetation C pool was composed of herbaceous plants and shrubs, and was estimated based on data obtained from Birdsey (1992). The growth of understorey vegetation increased rapidly after a disturbance, but then decreased with tree canopy closure. As the forest stand matured, the growth of understorey vegetation again increased as gaps in the canopy occurred from tree mortality.

The contributions of woody debris to C storage were a function of mortality and decomposition rates as modelled by Harmon (1993). Woody debris consisted of standing dead boles, stumps, dead roots (>2 mm in diameter), and dead branches (>2 cm in diameter) lying on the forest floor. Initial starting values were the amount of woody debris left on-site after whole-bole harvesting, assuming average stocking rates and standard rotation age. Consequently, woody-debris C initially decreased in size as the forest stand matured, but then increased with tree mortality.

The forest-floor C pool consisted of plant material that could not be classified as woody debris or understorey vegetation. Data on initial starting values and subsequent C-pool dynamics were obtained from published studies (e.g., Vogt *et al.*, 1986; Birdsey, 1992). Generally, forest-floor C increased with increasing stand age.

The starting level for forestland and grassland soil C was derived from a spatially explicit soil map developed by Kern (1994). Forest distributions from Eyre (1980) were used as an overlay on this map to give a mean soil C content to 1 m depth by forest. Initial soil C was assumed to be 50% of the mapped value of each forest type. Soil C then increased linearly to its mapped state (100%) over the course of one full harvest-rotation period. Grassland soil C began at 50% of the mean value to a 1 m depth; and increased linearly to reach 100% of the mean value over a 100-year period. These patterns of C gains or losses are based on field studies suggesting significant reductions when land-cover changes from native vegetation to cropland, and increases in C with the conversion of cropland back to native vegetation (Johnson, 1992; Cole *et al.*, 1993; Gebhart *et al.*, 1994). Typically, soil C losses are on the order of 10 to 50% in the temperate zone when native vegetation is converted to cropland.

Flux is the transfer of C between the forestland or grassland and the atmosphere in either direction and C loss due to tree harvesting or land-cover change. Positive values represent net C flux into forestland or grassland, while negative values show C loss. Total C in the various pools at the end of each decade was calculated by combining the age-class distribution in years with stand-level C budgets for forestland, or plot-level soil C budgets for grassland. Net annual flux was defined as the average change in C since the previous decade divided by 10 years.

Modelled scenarios

The C dynamics of the CRP was simulated for three possible outcomes as contracts begin to expire in 1996. The three scenarios reflect different assumptions about future CRP land area. The year 1985 represented the base where initial soil C of the grassland and forestland was calculated prior to grass and tree establishment. Actual land enrolment began in 1986 and, for this analysis, was assumed to continue through 1995. The program reached 16.2×10^6 ha by 1995, with 14.7×10^6 ha of grassland and 1.5×10^6 ha of forestland (Table 1). The allocations of land among forest types, growth and yield tables, and stand-level C budgets was assumed to be the same as the Parks and Hardie \$220 million afforestation scenario (Parks & Hardie, 1992).

The CRP1 scenario simulated the likely outcome of the CRP as current contracts expired at the end of the 10-year lease period (Osborn, 1993). As contracts began to expire

TABLE 1. Land area of the Conservation Reserve Program*.

	Area (ha)			
	Year 1986–1995	Year 2005–2035		
Region	All scenarios	CRP1	CRP2	CRP3
North-Central Central	6,209,234	2,568,503	6,209,234	6,376,924
North-Central Lake	1,260,161	541,692	1,260,161	1,467,025
Northeast	97,421	42,009	97,421	114,526
Pacific-Northwest West	645,054	265,672	645,054	652,652
Pacific Southwest	78,671	32,577	78,671	81,085
Rocky Mountain	2,748,868	1,129,254	2,748,868	2,756,743
South Central	3,933,125	1,826,875	3,933,125	5,731,632
Southeast	1,227,466	721,419	1,227,466	3,069,412
Total	16,200,000	7,128,001	16,200,000	20,249,999

*Data source: Center for Agricultural and Rural Development, Iowa State University, Ames, Iowa.

in 1996, 8.7×10^6 ha of grassland and 0.4×10^6 ha of forestland were returned to crop production over the next 10 years at a rate of 10% yr^{-1}. All aboveground and soil C accumulated between 1986 and 1995 was returned to the atmosphere when the land reverted to crop production. The original C content (year 1985) was maintained in the respective grassland or forestland soil pool throughout the simulation. The CRP2 scenario followed CRP1 in that the goal of 16.2×10^6 ha was reached by 1995. However, all contracts were renewed with no land returning to crop production. The CRP3 scenario was an expansion of CRP2 to include 4.0×10^6 ha of new forestland. The addition of new land occurred between the years 1996 and 2005 at a rate of 10% yr^{-1}.

Offsetting C emissions

GHG emissions for the United States are reported in the CCAP to be 1462 and 1568 TgCE for the years 1990 and 2000, respectively (Clinton & Gore, 1993). Regional emissions for 1990 and 2000 were calculated by scaling 1985 state estimates (Piccot & Saeger, 1990) to the national level presented in the CCAP and aggregating by region. The C-offset necessary to meet the CCAP goal in each region was calculated as 7% of 1990 regional GHG emissions.

RESULTS

CRP1 scenario

Simulated total C in the CRP land in 1985 was 949 TgC divided between the grassland (94%) and the forestland (6%) soil (Fig. 1a). Average C density per unit area was 6 kgC m^{-2}. Total C was estimated to increase 43% by the year 2035 to 1355 TgC. Grassland soil was the largest pool (79%) followed by tree (11%), forestland soil (8%), woody debris (1%), understorey vegetation (<1%), and forest floor (<1%). Average C density in forestland (19 kgC m^{-2}) was almost three times that in grassland (7 kgC m^{-2}).

Net C flux was projected to be the greatest during the 2006–2015 decade and the least during 1996–2005 (Fig. 1b). In this simulation, the grassland soil was a C sink during the first decade and then a source in the second decade as a large proportion of land was returned to crop production. In the following decades, grassland soil was once again a sink because the proportion that remained continued to sequester C. On forestland, the tree, woody debris, forest floor and soil compartments were all C sinks throughout the simulation. Because the forestland had nearly completed one standard rotation by 2035, the simulated soil compartment had recovered nearly all of its potential C. The understorey vegetation was a C sink during the first decade and thereafter a source, probably in response to elevated plant respiration and decreased photosynthesis due to competition from growing trees.

Average net C flux for the 50-year simulation was 8 TgC yr^{-1} for all C pools. The largest net flux was into grassland at 4 TgC yr^{-1}. Forestland C flux partitioned by pool was 3, 0.8, 0.4, <0.1, and 0.2 TgC yr^{-1}, for tree, soil, woody debris, understorey vegetation, and forest floor, respectively. The 50-year average sequestration rates for grassland and forestland were 24 and 298 gC m^{-2}, respectively.

CRP2 scenario

Total C increased 79% from 949 to 1699 TgC during the 50-year simulation (Fig. 2a). The partitioning among the C pools was similar to that modelled in the CRP1 scenario. Average C content per unit area for grassland and forestland was calculated to be 9 and 24 kgC m^{-2}, respectively.

C sequestration was projected to be the greatest during the 2006–2015 decade and least in the 1986–1995 period (Fig. 2b). The grassland and forestland soil, tree, forest floor, and woody debris pools were C sinks throughout the 50-year period. However, understorey vegetation was a C sink during the first decade and thereafter a small source.

The 50-year average net flux during the simulation was 15 TgC yr^{-1}. The largest net flux was projected to be into the grassland soil at 9 TgC yr^{-1}. Forestland C flux parti-

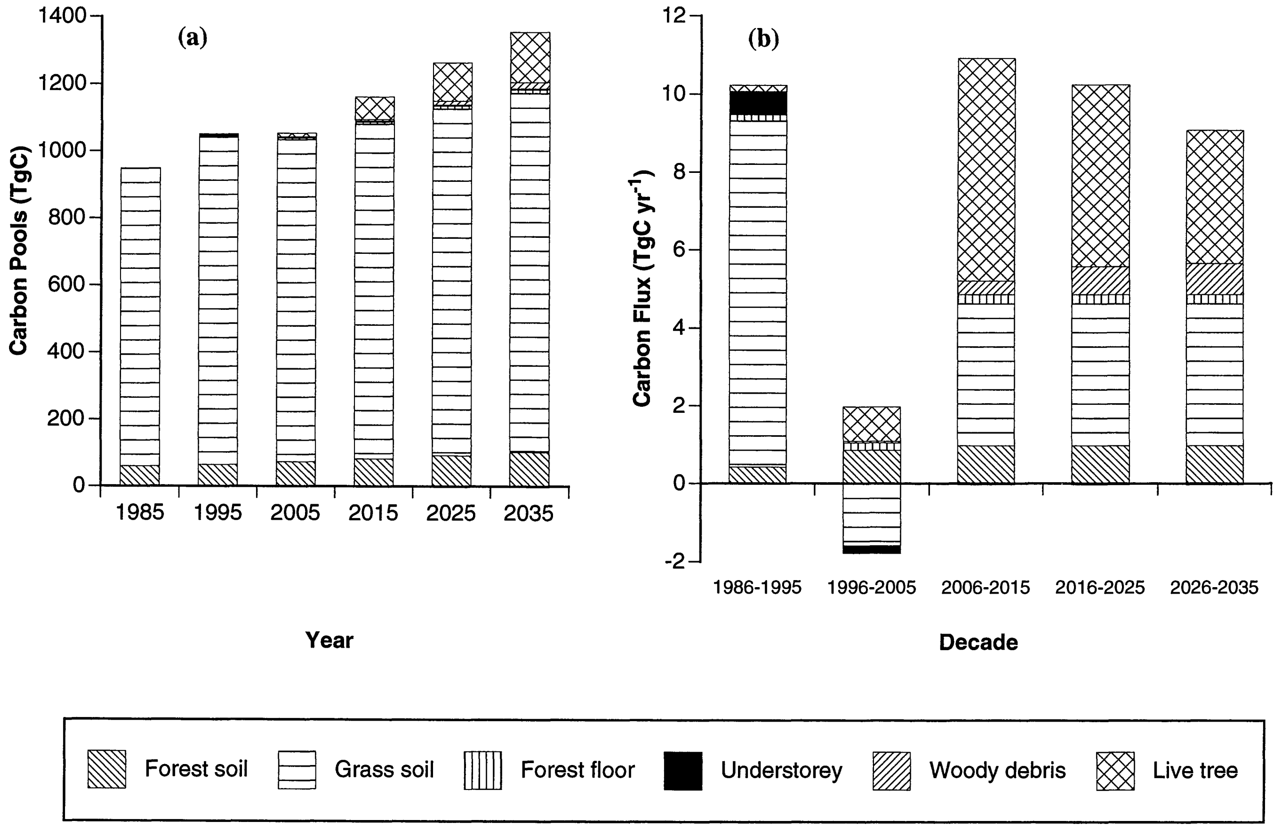

FIG. 1. (a) Simulated CRP1 C pools for 1985–2035. (b) Average annual net C flux projections for CRP1 by 10-year intervals. Positive or negative values are respectively net C gains or losses.

TABLE 2. Percentage of CRP land area and C sequestration under the CRP1 scenario for the year 2035.

Region	Grassland (%)	Forestland (%)	C sequestration (%)
North-Central Central	35	< 1	21
North-Central Lake	7	< 1	5
Northeast	< 1	< 1	< 1
Pacific-Northwest West	4	< 1	2
Pacific Southwest	< 1	< 1	< 1
Rocky Mountain	16	< 1	8
South Central	19	7	37
Southeast	3	7	26
Total	85	15	100

tioned by pool was 4, 1, 0.5, <0.1, and 0.3 TgC yr^{-1}, for tree, soil, woody debris, understorey vegetation, and forest floor, respectively. The 50-year average sequestration rates for grassland and forestland were calculated to be 61 and 408 gC m^{-2} yr^{-1}, respectively.

CRP3 scenario

Carbon content of the CRP land increased from 949 to 2489 TgC during the 50-year simulation (Fig. 3a). However, this increase included 163 TgC in the soil from the 4.0 Mha added during the second decade. Thus, C sequestered under this scenario was 2326 TgC, a 145% increase. (Fig. 3a). In the year 2035, the majority of C resided in the grassland and forestland soil at 54 and 16%, respectively. Trees accounted for 25% of C, followed by woody debris (3%), understorey (<1%)

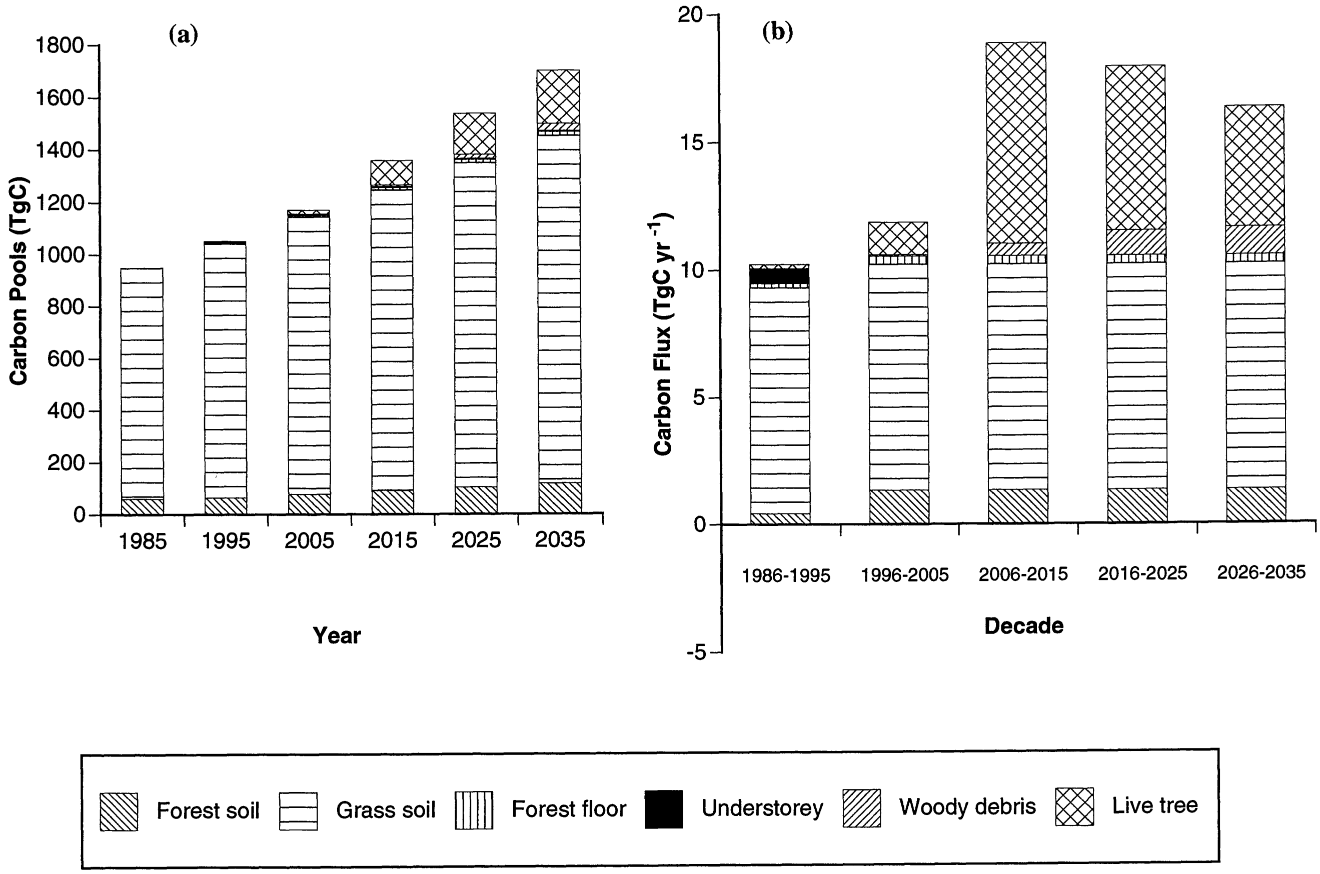

FIG. 2. (a) Simulated CRP2 C pools for 1985–2035. (b) Average net annual C flux projections for CRP2 by 10-year intervals. Positive or negative values are respectively net C gains or losses.

and forest floor (2%). Average C density per unit area was 9 and 20 kgC m^{-2} for the grassland and forestland, respectively.

C flux was projected to be the greatest during the 2016–2025 period and the least in the first decade (Fig. 3b). The grass and forest soil, tree, forest floor and woody debris pools were all consistently C sinks. The understorey vegetation was a sink for the first 20 years and thereafter a source. The tree pool at first was a minor C sink but increased in strength during the last 30 years as tree growth accelerated. The woody debris pool also grew during the simulation because of an increase in dead branches and trees that entered this compartment.

The modelled 50-year average net flux was 31 TgC yr^{-1}. The largest net flux of C was into the tree pool at 12 TgC yr^{-1}. C also accumulated in grassland and forestland soil at 9 and 7 TgC yr^{-1}, respectively. Net C accumulation in the forest floor, understorey, and woody debris was respectively 0.6, 0.3, and 1 TgC yr^{-1}. The simulated 50-year average rates of C sequestration for the grassland and forestland were 61 and 336 gC m^{-2} yr^{-1}, respectively.

Regional C sequestration

The CRP1 results are presented since this scenario represents the most likely outcome of the CRP. Carbon sequestration during the 50-year simulation varied by region as a result of land-area enrolment and the proportioning of grassland and forestland. For example, the South-Central and Southeast Regions sequestered 37% and 26% of total C respectively, because of the high proportion of forestland in these regions (Table 2). The South-Central Region sequestered more C than the Southeast because of its larger amount of grassland. The North-Central Central Region sequestered 21% of total C because its large expanse of grassland compensated for its lack of forestland. On the other hand, the Pacific Southwest and Northeast Regions both sequestered $<1\%$ total C because of the small land base they contributed to the CRP. In those regions with a relatively high proportion of forestland such as the South Central and Southeast, trees dominated C sequestration (Fig. 4). On the other hand, in those regions with little or no forestland such as the North-Central Central and Rocky Mountain, grassland soil dominated C sequestration.

Offsetting C emissions

Projected average net annual C gains during 1996–2005 were respectively <1, 12 and 16 TgC yr^{-1} for the CRP1, CRP2, and CRP3. The 50-year average net C gains for the

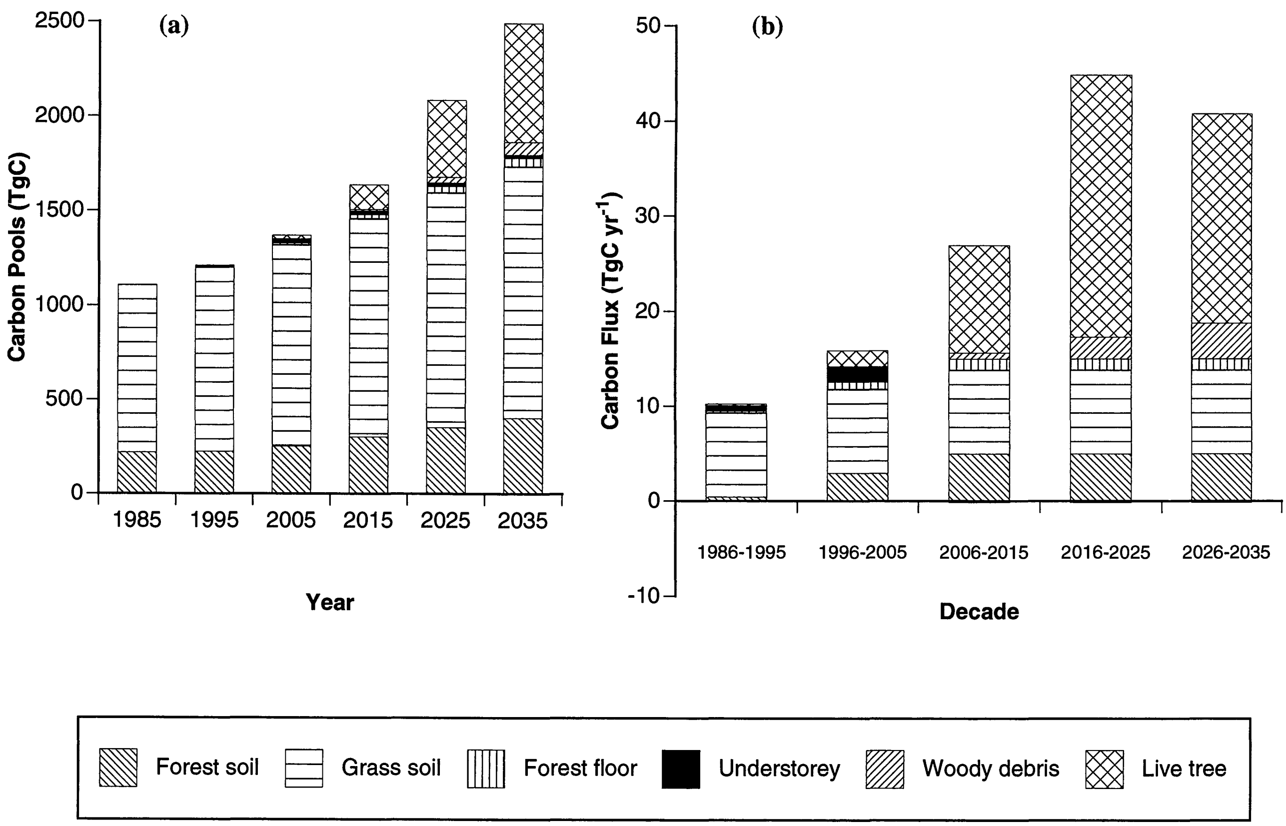

FIG. 3. (a) Simulated CRP3 C pools for 1985 through 2035. The forest soil pool for 1985 and 1995 are 163 TgC larger than for CRP1 and CRP2 because CRP3 includes cropland that has been converted to forestland in the 10-year period 1996–2005. (b) Average annual net C flux projections for the CRP3 by 10-year intervals. Positive or negative values are respectively net C gains or losses.

CRP1, CRP2, and CRP3 were 8, 15, and 31 TgC yr^{-1}, respectively (Table 3). These gains provide a measure of the long-term C benefit of the CRP in relationship with the CCAP. For example, CRP2 and CRP3 provide about 14% and 29%, respectively, of the offset required to maintain the CCAP goal for 50 years. The 50-year average flux is larger than the 1996–2005 flux because (1) most of the C lost from CRP land reverting to cropland occurs during this decade, and (2) trees planted under CRP3 are still small, so that the most rapid growth will occur in subsequent decades.

The importance of the CRP in off-setting GHG emissions varied among regions as illustrated by their 50-year average annual C gain (Table 3). For example, the CRP3 scenario provides about 76% of the C-offset target in the Southeast, 46% in the South Central, and only about 1% in the Pacific Southwest.

DISCUSSION

The conversion of land cover from native vegetation to crops has a strong influence on terrestrial C dynamics, for the most part acting as a C source (Post *et al.*, 1990; Dixon *et al.*, 1994; Barker *et al.*, 1995). However, in the eastern United States reforestation of abandoned agricultural land during the early to mid-decades of this century created a C sink (Heath and Birdsey, 1993). More recently, a decline in the area of private timberland is moderating this sink (Alig *et al.*, 1990). Consequently, programs such as the CRP that promote afforestation of environmentally sensitive cropland can augment C sequestration (Cubbage, 1992; Sampson, 1993).

Many agricultural soils are probably losing C in the course of normal tillage (Mann, 1986). However, the conversion of cropland to grassland or forestland as promoted by the CRP will counteract C loss to the atmosphere (Cubbage, 1992). For example, Gebhart *et al.* (1994) found that the soil-organic C level for cropland was 35% less than for native pasture across sites in Texas, Kansas, and Nebraska. In contrast, soil-organic C levels in grasslands that had been enrolled in CRP for 5 years was only 28% less than for native pastures.

The CRP scenarios examined in this study permit a comparison of C dynamics as influenced by land use. The return of 56% of the CRP1 land to crop production after contracts expired in 1996 resulted in reduced C pools and sequestration rates in comparison with CRP2 and CRP3. The C pools for CRP2 and CRP3 were respectively 25%

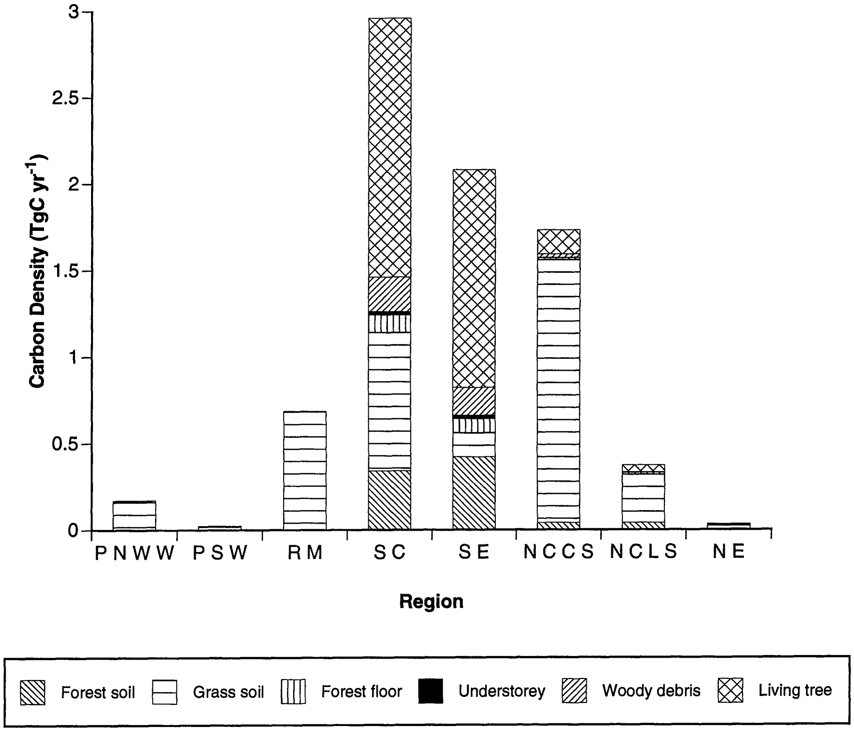

FIG. 4. Projected CRP1 50-year average net annual C flux: Pacific-Northwest West (PNWW); Pacific Southwest (PSW); Rocky Mountain (RM); South Central (SC); Southeast (SE); North-Central Central States (NCCS); North-Central Lake States (NCLS); Northeast (NE). Positive or negative values are respectively net C gains or losses.

TABLE 3. C emissions, offsets, and 50-year average net gains.

Region	1990 emissions (TgCE yr^{-1})*	C offset goal (TgCE yr^{-1})†	50-year average net C gain (TgC yr^{-1})		
			CRP1	CRP2	CRP3
North-Central Central	422	30	1.7	4.0	4.9
North-Central Lake	35	2	0.4	0.8	1.5
Northeast	244	18	<0.1	0.1	0.1
Pacific-Northwest West	26	2	0.2	0.4	0.3
Pacific Southwest	120	9	<0.1	0.1	0.1
Rocky Mountain	114	8	0.7	1.7	1.8
South Central	338	25	3.0	5.0	12.3
Southeast	162	12	2.1	3.0	9.8
Total	1,462	106	8.1	15.1	30.8

*Based on 1985 GHG emissions (Piccot & Saeger, 1990) scaled to the 1990 GHG emissions presented in the CCAP (Clinton & Gore, 1994).

†Based on the CCAP (Clinton & Gore, 1994).

and 84% larger than CRP1 in 2035. Also, the 50-year average net C sequestration per unit area per year was respectively 85% and 172% greater for CRP2 and CRP3 compared with CRP1. The return of grassland to crop production under the CRP1 scenario resulted in a large flux of C to the atmosphere in response to increased soil respiration, increased organic-matter decomposition, and decreased organic matter input from vegetation (Kern & Johnson, 1993; Lee, Phillips, & Liu, 1993). However, the remaining CRP1 land left in grass production was a C sink (Gebhart *et al.*, 1994).

Evaluation of CRP2 allows a comparison of C-sequestration potential for grassland and forestland for the entire 50 years since the land base does not change in this scenario as it does in CRP1 and CRP3. During the 50-year simulation, forestland sequestered seven times more C per unit area per year than grassland. The greater growth and C storage capacity of trees and accumulation of woody debris compared with herbaceous vegetation explains the difference. Trees and woody debris are important C sinks in many U.S. forests as Heath & Birdsey (1993) and Turner *et al.* (1993, 1995b) demonstrated.

The CRP3 scenario illustrates the C benefit of increasing the forestland component of the CRP by 25%. Total C storage increased 46% by the year 2035 in comparison with CRP2. However, the rate of C sequestration for CRP3 forestland was 18% less than CRP2 forestland because of the small size of the trees planted on the land added during the second decade. The C-sequestration potential of these trees should greatly increase as they continue to grow in subsequent years.

The simulations suggest that adoption of a vigorous afforestation effort on environmentally sensitive cropland as under the CRP3 could provide about 15% of the needed C offset to attain the CCAP. Maintaining land in the CRP as in the CRP2 scenario would provide about 11% of the needed C offset. However, if CRP land is returned to crop production as simulated under CRP1, then a $<1\%$ C benefit would be realized in relationship to the CCAP.

The CRP has already made history: during 1987–1991 over 1.0×10^6 ha of environmentally sensitive cropland was planted with trees (Sampson, 1993). This was the highest reforestation effort ever occurring in the United States. The CRP fell short of its anticipated tree-planting goal because many land owners elected to plant their land into grass. Similar programs in the future could provide strong incentives to encourage tree planting to maximize C sequestration and long-term storage. Some ancillary benefits may also include improved wildlife habitat and decreased soil erosion (Osborn, 1993).

Another possible C benefit of the CRP in addition to sequestration is the production of biofuels such as ethanol or fuelwood (Brown, Flavin & Postel, 1990; Sampson, 1993). However, this option needs to be fully explored. Biofuels contain C that was recently removed from the atmosphere through plant photosynthesis and will be returned upon combustion. Eventually an equilibrium will be established between C sequestration by vegetation and C emission through fuel combustion (Barker *et al.*, 1995). Conversely, fossil fuels store inert C that was sequestered millions of years ago, and therefore, release 'new' C into the atmosphere upon combustion. Brown *et al.* (1990) calculated that if all the CRP land were planted with trees, approximately 4.2×10^7 m^3 yr^{-1} (10% of current gasoline consumed annually in the United States) of ethanol could be produced through a sustainable program of tree harvesting and reforestation. In another study that evaluated management options to improve C sequestration of forests in the southeast United States, Barker *et al.* (1995) projected that harvesting trees for fuelwood production with subsequent reforestation could result in 1.1 GgC yr^{-1} average net C gain over 50 years.

Model evaluation

The modelling framework, assumptions, and databases used for these simulations are supported by scientific literature (as referenced) and current monitoring of U.S. forests. The modelling framework was based on procedures developed by Turner *et al.* (1993; 1994, 1995) to evaluate the C dynamics of the U.S. forest sector. Their projections of C sequestration compared favourably with those of other researchers (Birdsey, 1992; Powell *et al.*, 1993; Heath & Birdsey, 1993). Furthermore, Barker *et al.* (1995) used a similar modelling approach to evaluate management influence on C dynamics of forests in the southeast United States with C density estimates agreeing with calculations by the American Forestry Association (1992). The forest-stand growth and yield tables of ATLAS were based on repeated measurements of a set of permanent plots maintained by FS Inventory and Analysis Units (USDA, 1992). Actual long-term, field monitoring of CRP grassland and forestland would provide data to validate C pools and sequestration rates. Such information would also be useful to plan other programs targeted for C sequestration and conservation to offset GHG emissions.

ACKNOWLEDGMENTS

Thanks is extended to J. Smith for reviewing a draft manuscript. The research described in this article has been funded by the U.S. Environmental Protection Agency. This document has been prepared at the EPA Environmental Research Laboratory in Corvallis, OR, through contract 68-C8-0006 to ManTech Environmental Research Services Corp. It has been subjected to the Agency's peer review and administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

Alig, R.J., Hohenstein, W.G., Murray, B.C. & Haight, R.G. (1990) *Changes in area of timberland in the United States, 1952–2040, by ownership, forest type, region, and state*. General Technical Report SE-64. U.S. Department of Agriculture, Forest Service, Washington, DC.

American Forestry Association (1992) *Enhancing management of forests and vegetation on Department of Defense lands: opportunities, benefits, and feasibility*. PM-221, U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC.

Barker, J.R., Baumgardner, G.A., Lee, J.J. & McFarlane, J.C. (1995) *Carbon sequestration and forest management at DOD Installations: an exploratory study*. EPA/600/R-95/037. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Birdsey, R.A. (1992) *Carbon storage and accumulation in the United States forest ecosystems*. General Technical Report WO-59. U.S. Department of Agriculture Forest Service, Washington, DC.

Brown, L.R., Flavin, C. & Postel, S. (1990) Picturing a sustainable society. *State of the world: 1990* (ed. by L. Starke), pp. 173–190. W.W. Norton, New York.

Clinton, W.J. & Gore, Jr, A. (1993) *The Climate Change Action Plan*. The White House, Washington, DC.

Cole, C.V., Flach, K., Lee, J., Sauerbeck, D. & Stewart, B. (1993) Agricultural sources and sinks of carbon. *Water, Air Soil Pollut.* **70**, 111–122.

Cost, N.D., Howard, J.O., Mead, B., McWilliams, W.H., Smith, W.B., VanHooser, D.D. & Warton, E.H. (1990) *The Biomass resource of the United States*. General Technical Report WO-57, U.S. Department of Agriculture Forest Service, Washington, DC.

Cubbage, F.C. (1992) Federal land conversion programs. *Forest and global change, Volume 1: opportunities for increasing forest cover* (ed. by R.N. Sampson and D. Hairages), pp. 177–194. American Forests, Washington.

Dixon, R.K., Brown, S. Houghton, R.A., Solomon, A.M., Trexler, M.C. & Wisniewski, J. (1994) Carbon pools and flux of global forest ecosystems. *Science*, **263**, 195–190.

Eyre, F.H. (1980) *Forest cover types of the United States and Canada*. Society of American Foresters, Washington.

Gebhart, D.L., Johnson, H.B., Mayeux, H.S. & Polley, H.H. (1994) The Conservation Reserve Program increases soil organic carbon content. *J. Soil Water Conserv*. **49,** 488–492.

Harmon, M. (1993) Woody debris budgets for selected forest types in the US. *The forest sector carbon budget of the United States: carbon pools and flux under alternative policy options* (ed. by D.P. Turner, J.J. Lee, G.J. Koerper, and J.R. Barker), pp. 151–178. EPA/600/3-93/093. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

Haynes, R.W. (1990) *An analysis of the timber situation in the United States: 1989–2040*. General Technical Report RM-199. United States Department of Agriculture, Forest Service, Washington.

Heath, L.S. & Birdsey, R.A. (1993) Carbon trends of productive temperate forests of the coterminous United States. *Water, Air Soil Pollut*. **70**, 279–293.

Heath, L.S., Kauppi, P.E., Burschel, P., Gregor, H-D., Guderian, R., Kohlmaier, G.H., Lorenz, S., Overdieck, D., Scholz, F., Thomasius, H. & Weber, M. (1993) Contribution of temperate forests to the world's carbon budget. *Water, Air Soil Pollut*. **70**, 55–69.

Johnson, D.W. (1992) Effects of forest management on soil carbon storage. *Water, Air Soil Pollut*. **64**, 83–120.

Kern, J.S. & Johnson, M.G. (1993) Conservation tillage and impacts on national soil and atmospheric carbon levels. *Soil Sci. Soc. Am. J.* **57**, 200–210.

Kern, J. (1994) Spatial patterns of soil organic carbon in the contiguous United States. *Soil Sci. Soc. Am. J.* **58,** 439–455.

Lee, J.J., Phillips. D.L. & Liu, R. (1993) The effects of trends in tillage practices on erosion and carbon content of soils in the US corn belt. *Water, Air Soil Pollut*. **70**, 389–402.

Mann, L.K. (1986) Changes in soil carbon storage after cultivation. *Soil Sci*. **142**, 279–288.

Mills, J.R. & Kincaid, J.C. (1992) *The aggregate timberland assessment system—ATLAS: A comprehensive timber projection model*. General Technical Report PNW-GTRR-281. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, OR.

Ojima, D.S., Dirks, B.O.M., Glenn, E.P., Owensby, C.E. & Scurlock, J.O. (1993) Assessment of C budget for grasslands and drylands of the world. *Water, Air Soil Pollut*. **70**, 95–110.

Osborn, T. (1993) The Conservation Reserve Program: status, future, and policy options. *J. Soil Water Conserv*. **48**, 272–279.

Parks, P.J. & Hardie, I.W. (1992) *Least-cost forest carbon reserves: cost-effective subsidies to convert marginal agricultural land to forests*. American Forestry Association, Washington.

Piccot, S. & Saeger, M. (1990) *National- and state-level emissions estimates of radiatively important trace gases (RITGs) from anthropogenic sources*, 36 pp. EPA-600/8-90-073. U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC.

Post, W.M., Peng, T-H., Emanuel, W.R., King, A.W., Dale, V.H. & DeAngelis, D.L. (1990) The global carbon cycle. *Am. Sci*. **78**, 310–326.

Powell, D.S., Faulkner, J.L., Darr, D.R., Shu, Z. & MacCleery, D.W. (1993) *Forest resources of the United States, 1992*. General Technical Report RM-234. U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft Collins, CO.

Sampson, R.N. (1993) Forest management and biomass in the U.S.A. 1993. *Water, Air Soil Pollut*. **70**, 519–532.

Simpson, L.G. & Botkin, D.B. (1992) Vegetation, the global carbon cycle, and global measures. *The science of global change: the impact of human activities on the environment* (ed. D.A. Dunnette and R.J. O'Brien), pp. 413–425. American Chemical Society Symposium Series 483, American Chemical Society, Washington.

Thompson, M.T. (1989) *Forest statistics for Georgia, 1989*. Resource Bulletin SE-109, U.S. Department of Agriculture Forest Service, Washington, DC.

Turner, D.P., Koerper, G., Harmon, M. & Lee, J.J. (1995a) Carbon budgets for forests of the United States. *Ecol. Appl*. **5,** 421–436.

Turner, D.P., Koerper, G.J., Harmon, M. & Lee, J.J. (1995b) Carbon sequestration by forests of the United States: current status and projections to the year 2040. *Tellus*, **47B**, 1–2.

Turner, D.P., Lee, J.J., Koerper, G.J. & Barker, J.R. (1993) *The forest sector carbon budget of the United States: carbon pools and flux under alternative policy options*. EPA/600/3-93/093. U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, OR.

USDA (U.S. Department of Agriculture) (1992) *Forest Service resource inventories: an overview*. U.S. Department of Agriculture, Forest Service, Forest Inventory, Economics, and Recreation Research, Washington.

Vogt, K.A., Grier, C.C. & Vogt, D.J. (1986) Production, turnover, and nutrient dynamics of above- and below-ground detritus of world forests. *Adv. Ecol. Res*. **15,** 303–377.