December 20, 2014

To whom it may concern:

It is our pleasure to present the attached report: “An Overview of Carbon Storage and Utility for Various Types of Agricultural Biomass – Indiana.” The report provides an analysis of the possibility for implementing various biomasses for carbon uptake and sequestration/storage for the state of Indiana. The report was motivated by the release of the EPA’s Clean Power Plan, which aims to reduce greenhouse gas emissions from the electricity power sector. Indiana relies heavily on coal power plants, and may be significantly impacted by the new policy. This report explores alternatives to meet the plan’s goals.

One of the goals of the report was to be unambiguous and transparent in all information, calculations, and findings. The authors welcome comments and suggestions on the report. Please direct any comments, feedback, or questions to Julio Navarro at navarro8@purdue.edu.

Sincerely,

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Purdue University
An Overview of Carbon Storage and Utility for Various Types of Agricultural Biomass – Indiana

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December 2014
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Executive Summary

In June 2, 2014 the U.S. Environmental Protection Agency (EPA) announced a proposed policy change – the Clean Power Plan. The policy change calls for a reduction in the amount of greenhouse gas (GHG) emissions from the electricity power sector by 30% nationwide by 2030. In particular, the change calls for a reduction in CO₂ emissions from 1,500 lbs CO₂/MWh to 1,100 lbs CO₂/MWh.

Coal-fired power plants are important for electricity generation in the U.S. Many states are highly dependent on coal owing to its domestic abundance and low cost. Indiana is among the states that are the most dependent on coal-powered plants, and it is likely to be significantly affected by the proposed policy change. The policy lays out best management practices (BMPs) to reduce carbon emissions, and suggests four building blocks for a Best System of Emission Reduction (BSER): i) make fossil-fuel plants more efficient, ii) use more low-emitting power sources, iii) use renewable power, iv) use electricity more efficiently through demand-side changes. The policy allows for the possibility of alternative solutions.

Removal storage of atmospheric CO₂ represents one such alternative. This report examines the potential for carbon uptake and sequestration/storage into different biomass types in the state of Indiana. Specifically, the report examines native hardwoods (i.e., hickory, maple, oak and walnut); agricultural crops (i.e., corn and soybean); and dedicated energy crops (hybrid poplars, Miscanthus, and switchgrass). Each biomass type has its own disadvantages and disadvantages as summarized in the table below.

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Hardwoods</th>
<th>Agricultural Crops</th>
<th>Dedicated Energy Crops</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Corn</td>
<td>Soybean</td>
</tr>
<tr>
<td>Potential Uses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Marginal lands</td>
<td>• Marginal lands</td>
<td>• Marginal lands</td>
<td>• Marginal lands</td>
</tr>
<tr>
<td>• Wood products</td>
<td>• Stover co-firing</td>
<td>• Conversion to biofuel</td>
<td>• Stover co-firing</td>
</tr>
<tr>
<td>Carbon Benefits</td>
<td></td>
<td>• SOC increase</td>
<td>• SOC increase</td>
</tr>
<tr>
<td>• Long-term storage</td>
<td>• Carbon increase</td>
<td>• Carbon offsets</td>
<td>• Carbon offsets</td>
</tr>
<tr>
<td>• Closed-loop cycle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon Storage</td>
<td>8.0-10.6 ton CO₂/ac/yr</td>
<td>0.089-0.313 (^1) ton CO₂/ac/yr</td>
<td>14.1-20.2 (^2) ton CO₂/ac/yr</td>
</tr>
<tr>
<td>Estimated Costs</td>
<td>1.58-2.5 (^3) $/ton CO₂</td>
<td>10-25 (^4) $/ton CO₂</td>
<td>12.5-30.0 (^5) $/ton CO₂</td>
</tr>
<tr>
<td>Drawback</td>
<td></td>
<td>• Food vs. fuel tradeoff</td>
<td>• Food vs. fuel tradeoff</td>
</tr>
<tr>
<td>• Available land</td>
<td>• Time scale</td>
<td>• Time scale</td>
<td>• Storage until harvested for energy</td>
</tr>
<tr>
<td>• Payback period (^7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Slow growth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) For agricultural crops, storage is achieved with soil organic carbon (SOC); \(^2\) Storage until harvested for energy; \(^3\) Estimated using a 40-year growth period; \(^4\) Value estimated from emission trading markets, because implementation is impractical; \(^5\) Prices for annual harvest, but can have same applications as hardwoods and lower costs; \(^6\) Does not include revenue; and \(^7\) If end use is wood products
# Table of Contents

List of Tables ........................................................................................................ vi
List of Figures .......................................................................................................... vii
List of Acronyms and Abbreviations ...................................................................... viii

## 1.0 Introduction

- Motivation ............................................................................................................. 1
- Background .......................................................................................................... 2

### 1.1 Overview of Carbon Cycle

- Carbon in Biomass vs. Atmospheric CO$_2$ ......................................................... 6
- Terrestrial Sequestration .................................................................................... 6

### 1.2 Fossil Fuel and Electricity Generation

- CO$_2$ Emission Sources .................................................................................... 7

## 2.0 Forestry Measures for CO$_2$ Utilization

### 2.1 Overview of Carbon Cycle for Hardwoods

- Growth Cycle, Carbon Uptake, and Carbon Sequestration .............................. 13
- Residues, Thinnings, and Harvested Materials .................................................. 14

### 2.2 Land Issues and Yields

- Land Availability .................................................................................................. 15
- Rehabilitation of Marginal Lands ......................................................................... 16
- Planting Density .................................................................................................... 18
- End Use: Dimensional Lumber, Peeler Logs, Combustible Fuel ....................... 19
- Hardwood CO$_2$ Sequestration Potential in Response to EPA Policy Changes .... 21

### 2.3 Economic and Policy Implications

- Furniture Industry and Other Forest Product Companies ................................ 22
- Summary of CO$_2$ Benefits Relative to EPA Rule ............................................. 24

## 3.0 Agricultural Crops and their Residues for Carbon Utilization

### 3.1 Overview of Carbon Cycle for Agricultural Crops and Residues

- Types: Corn, Soybeans, and Stover ..................................................................... 26
- Growth Cycle, Carbon Uptake, and Sequestration ........................................... 26
- Data from Literature ............................................................................................. 27

### 3.2 Land Issues and Yields .................................................................................. 28
Land Usage ........................................................................................................................................... 29
Yields and Energy Content .................................................................................................................... 29
Utilization of Crops and Residues for Carbon Storage ....................................................................... 30
Conservation Agricultural Practices ...................................................................................................... 30
3. 3 Economic and Policy Implications ................................................................................................. 31
End-Uses of Corn and Soybeans: Food vs. Fuel ................................................................................... 34
Implications of Utilizing Residues as a Feedstock for Biofuel Production ............................................. 34
Summary of CO₂ Benefits from Responding to EPA Policy Changes .................................................. 34
4.0 Dedicated Energy Crops for Carbon Utilization ............................................................................. 35
4.1 Overview of Carbon Cycle for Dedicated Energy Crops ................................................................ 35
Crop Types ........................................................................................................................................... 36
Growth Cycle, Carbon Uptake, and Carbon Sequestration .................................................................... 37
4.2 Land Issues and Yields .................................................................................................................... 38
Land Availability ..................................................................................................................................... 39
Rehabilitation of Marginal Lands .......................................................................................................... 39
Yields and Energy Content .................................................................................................................... 39
Challenges: Harvesting, Storage, and Transportation ........................................................................... 40
4.3 Economic and Policy Implications ................................................................................................. 41
Implications for Power Plants, Co-firing Applications, and Biofuels ..................................................... 42
Conservation Reserve Program (CRP) ................................................................................................. 44
Summary of CO₂ Benefits Relative to EPA Rule .................................................................................. 45
5.0 Summary .......................................................................................................................................... 45
6.0 References ......................................................................................................................................... 48
List of Tables

Table 1. Power plant building blocks for BSER ................................................................. 1
Table 2. Radiative efficiency and GWPs for several GHGs ................................................. 6
Table 3. Soil carbon storage potential for different terrestrial land uses ............................... 7
Table 4. Electricity generation-related CO₂ emissions ......................................................... 9
Table 5. Carbon pools related to trees .................................................................................. 15
Table 6. Indiana forestland ownership by percentage in 2009 .............................................. 16
Table 7. Hardwood planting density and survival .................................................................... 19
Table 8. Example average service life of wood products ....................................................... 20
Table 9. Carbon sequestration potential for hardwoods ......................................................... 22
Table 10. Employment by Indiana manufacturing sectors in 2009 ......................................... 23
Table 11. Lumber prices in MBF from the Appalachian Market area .................................... 23
Table 12. Percentage of remaining residue per acre ............................................................. 30
Table 13. Factors affecting SOC associated with different energy crops ............................ 37
Table 14. Comparison of Miscanthus, corn, and short-rotation coppice ............................... 38
Table 15. Midwest site's average switchgrass yields .............................................................. 40
Table 16. Midwest and Northeast average Miscanthus yields ................................................ 40
Table 17. Annual field labor times requirements by crop system .......................................... 41
Table 18. Annualized production costs of perennials and row crops ..................................... 42
Table 19. Annualized costs for dedicated energy crops ......................................................... 43
Table 20. Estimated feedstock potential to meet biofuel needs ........................................... 44
List of Figures

Figure 1. Yearly changes in the level of atmospheric CO$_2$ .......................................................... 2
Figure 2. Historical changes in the level of atmospheric CO$_2$ ............................................................ 3
Figure 3. The carbon cycle.................................................................................................................. 5
Figure 4. U.S. CO$_2$ emissions by source .......................................................................................... 8
Figure 5. 2012 U.S. fossil fuel CO$_2$ combustion emissions by sector/fuel ........................................... 8
Figure 6. U.S. GHG emissions by sector with electricity distributed ................................................. 9
Figure 7. 2012 electricity net generation by source for 9 of the top 10 coal consuming states, with a lower coal consuming state ........................................................................................................ 10
Figure 8. U.S. GHG emissions in 2012 ............................................................................................ 10
Figure 9. U.S. GHG emissions by gas for years 1990-2012 ............................................................... 11
Figure 10. Carbon cycle for a single tree ......................................................................................... 12
Figure 11. Forest regions of the U.S. ............................................................................................... 13
Figure 12. Tree diversity in Indiana .................................................................................................. 14
Figure 13. Reasons landowners provide for planting ....................................................................... 17
Figure 14. Bear Run Mine ............................................................................................................... 18
Figure 15. Carbon cycle for wood products .................................................................................... 21
Figure 16. Agricultural crops C sequestration model ....................................................................... 25
Figure 17. U.S. domestic corn us for years 1980-2013 .................................................................. 27
Figure 18. GHGs emitted from certain agricultural production processes in 2012 ....................... 28
Figure 19. Corn, soybean and wheat yield trends in Illinois from 1990-2008 ............................. 28
Figure 20. Soybean-corn rotation effects on grain yield ................................................................. 29
Figure 21. Optimization of crop management practices to increase N availability and C sequestration potential ...................................................................................................................... 31
Figure 22. 2013 no-till soybean percentages by county for Indiana ............................................... 32
Figure 23. 2013 no-till corn percentages by county for Indiana ..................................................... 33
Figure 24. Energy plantation’s biofuels effects on C sequestration .............................................. 34
Figure 25. Herbaceous and wood crop possibilities by the U.S. DOE ......................................... 38
Figure 26. Energy balance for co-firing biomass with coal ........................................................... 43
List of Acronyms and Abbreviations

ac  acre (43,560 ft$^2$ or 4,046.86 m$^2$)
AMU  atomic mass unit
BMP  best management practice
BTU  British Thermal Unit (1055 J)
Bu  bushel
C  carbon
CO$_2$-Eq  Carbon dioxide equivalent (GWP x mass of GHG)
dbh  diameter at breast height
dry ton  (zero moisture content and 1.9 tons of green biomass)
Eq  equivalent
GHG  greenhouse gas
Gt  gigatonne ($10^9$ ton)
GWP  global warming potential
Hectare  10,000 m$^2$
kWh  kilowatt hour
Mt  megaton ($10^8$ tons)
MBF  thousand board foot (1 BF=volume of a board one foot long, one foot wide and one inch thick)
Mac  million acre
Mha  million hectare
mg  milligram
Mg  megagram
Mt  mega tonne (metric ton) equal to $10^6$ tons
mi  mile
MJ  mega joule
MWh  megawatt hour
Pg  Petagram ($10^{15}$ g or $10^{12}$ kg)
ppb  parts per billion
ppm  parts per million
QUAD $10^{15}$ BTU (1.055 x $10^{18}$J or 1.055 x $10^{12}$MJ)
RBP  recommended best practice
T  Short Ton (1 short ton equals 2,000 lbs or 907.185 kg)
SOC  soil organic carbon
Tg  teragrams ($10^{12}$ g or $10^9$ kg or $10^6$ metric tons)
ton  tonne or metric ton (1,000 kg or $10^6$ g)
W  watt
1.0 Introduction

Motivation

In 2009, the U.S. Environmental Protection Agency (EPA), under section 202(a) of the Clean Air Act, stated that the public’s health and the welfare of current and future generations is being endangered by the combination of six greenhouse gases (GHGs) [U.S. EPA, 2014a]. One GHG in particular, carbon dioxide (CO₂), was said to be a major contributor to human-induced climate change. Due to the U.S.’s large GHG emissions associated with fossil-fuel combustion, the EPA, under order from President Obama, proposed a plan to cut carbon emissions from power plants. On June 2, 2014, the proposed Clean Power Plan was released to the public for comment. The plan establishes carbon emissions standards for certain existing, modified or reconstructed, and new power plants. The plan’s goal is to cut carbon emissions from the power sector 30% nationwide by 2030 [U.S. EPA, 2014a].

The EPA indicates that the Clean Power Plan will protect the public’s health and welfare while maintaining an affordable and reliable energy system [U.S. EPA, 2014b]. The plan is built around a national framework, Best System of Emission Reduction (BSER), focused on giving states flexibility in choosing individualized best management practices (BMPs) to reduce carbon emissions. The BSER establishes goals for each state and it will be up to the state to develop an implementation plan to meet those goals. The BSER is based on four “building blocks” (Table 1): a) improvement in efficiency of existing power plants, b) utilization of existing low-emission power sources, c) construction of low- and zero-emission energy sources, and d) increase end-user energy efficiency [U.S. EPA, 2014c]. In addition, the states will be able to use other measures not specified by the EPA.

Many states have already established emission-reduction measures and under the Clean Power Plan they will be able to build upon these. States that propose new measures will need EPA approval for them. The EPA was accepting comments on the proposed plan until December 1, 2014. The EPA must receive an initial submission of a state’s plan by June 20, 2016, with an extension being offered under certain circumstances.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Building Block</th>
<th>Value Allocated in Goal Setting Formula</th>
<th>Expected Cost ($·ton CO₂)</th>
<th>% of BSER CO₂ Reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EI-EGUs</td>
<td>Make fossil fuel plants more efficient</td>
<td>6% average heat rate improvement for coal steam electric generating units (EGUs)</td>
<td>6-12</td>
<td>12</td>
</tr>
<tr>
<td>LEPS</td>
<td>Use more low-emitting power sources</td>
<td>Send to existing/under construction natural gas combined cycle units to up to 70% capacity factor</td>
<td>30</td>
<td>31</td>
</tr>
<tr>
<td>RENEW</td>
<td>Use more zero and low-emitting power sources</td>
<td>Send to new clean, new nuclear, check deployment of new renewable, and extend existing nuclear use</td>
<td>10-40</td>
<td>40</td>
</tr>
<tr>
<td>DSM</td>
<td>Use electricity more efficiently</td>
<td>Increase demand-side energy efficiency to 1.5% annually</td>
<td>16-24</td>
<td>18</td>
</tr>
</tbody>
</table>
Background

Since the industrial revolution, atmospheric levels of CO\(_2\) have increased. According to IPCC [2013], the fluxes and pools in the carbon cycle have been altered through human activity, most notably the increase in CO\(_2\) concentration in the atmosphere. The higher concentrations of CO\(_2\) are altering the balance of the natural carbon cycle and there is an increasing amount of scientific evidence supporting the notion that higher CO\(_2\) concentrations are acting as a catalyst for global climate change. Mounting scientific evidence suggests that the increase in atmospheric CO\(_2\) concentrations is largely due to anthropogenic fossil-fuel combustion and land-use change, including deforestation, and agricultural cultivation [IPCC, 2000; IPCC, 2007; IPCC, 2013].

Evidence for increases in CO\(_2\) concentrations can be seen in Figure 1, which represents the daily CO\(_2\) concentrations recorded at Mauna Loa, Hawaii, by the National Oceanic and Atmospheric Administration (NOAA). In the graph, each point represents a day, each red line indicates a week and a blue line indicates a month. When comparing the CO\(_2\) concentrations from July 2013 to July 2014, the evidence of an increasing atmospheric CO\(_2\) concentration is clear. When looking at temporal changes in CO\(_2\) concentrations since 1959 at Mauna Loa, an overall upward trend is observed. This trend begins below 320 ppm and rises to the current level of more than 400 ppm (Figure 2).

![One year of CO\(_2\) daily and weekly means at Mauna Loa](image)

**Figure 1. Yearly changes in the level of atmospheric CO\(_2\) [NOAA, 2014]**
Atmospheric CO$_2$ is an important part of the global carbon cycle, where carbon travels between the earth’s natural carbon pools: the atmosphere, the land, and the oceans [NASA, 2011]. The ability of each pool to absorb and cycle CO$_2$ has limits, which prevents each pool from achieving balance when large increases of CO$_2$ are introduced into one of the pools. Currently high concentrations of CO$_2$ in the atmosphere are not being cycled rapidly enough for equilibrium to be achieved in the carbon cycle [U.S. DOE, 2008]. This imbalanced has led to some pool concentrations to increase to higher levels than others, such as the atmospheric pool. There is now a need to decrease CO$_2$ emissions and stabilize its atmospheric levels. The introduction of two groups of strategies has stemmed from this need: the reduction of CO$_2$ emissions, either through a decrease in fossil-fuel usage or an increase in efficiency and the capture and storage of CO$_2$ (e.g., carbon sequestration) [Shrag, 2007]. Many strategies within these two groups offer a means to reduce emissions and atmospheric, terrestrial, and oceanic concentrations. However, none of the strategies offer a permanent solution, which would require halting increases in atmospheric CO$_2$ concentrations, restoring balance in the carbon cycle over time.

Carbon dioxide capture and storage strategies can be divided into two categories: biotic and abiotic sequestration. Biotic sequestration involves the capture of CO$_2$ with photoautotrophs through the process of photosynthesis and the storage of the captured carbon in living tissues. Abiotic sequestration is a concept that is based on the capture of carbon without the direct use of living organisms [Lal, 2008]. A promising technology for abiotic sequestration involves directly capturing CO$_2$ at the point of emission and injecting it into deep underground geologic formations. As is the case with many abiotic sequestration technologies, they are experimental and need to be studied and tested before being implemented on a large scale [U.S. EPA, 2014c].

According to Lal [2008], biotic sequestration offers great potential because it is based on a natural process and is dependent on management options. Biotic sequestration can be further divided into two main categories, oceanic and terrestrial. Biotic, oceanic, and terrestrial sequestrations rely on the process of photosynthesis to capture CO$_2$. The oceans are the largest active pool of CO$_2$ and thus offer the largest potential for sequestration [IPCC, 2013]. Carbon
sinks, or pools, are reservoirs where carbon can accumulate and be stored for an indefinite period of time. Oceanic sequestration strategies include the injection of CO$_2$ deep into the ocean and the fertilization of the ocean with nutrients to increase phytoplankton growth [Herzog, 1998]. Terrestrial sequestration is the use of vegetative biomass and soil to capture and store CO$_2$. The U.S. DOE-NETL [2010] states that these strategies also offer great potential, as they can be quickly implemented, offer conservative management of forests and agricultural lands, and have secondary benefits associated with them (i.e., improved ecosystems and increased crop production). This report will present the tradeoffs associated with various types of terrestrial sequestration, focusing on agricultural biomass related carbon-management strategies.

1.1 Overview of Carbon Cycle

Carbon is the foundation of life on earth and can be found in organic and inorganic forms. The carbon cycle can be divided into slow and fast cycles. In the slow cycle, carbon moves between the atmosphere, oceans, soils, and rocks over millions of years. Atmospheric carbon falls to the earth as carbonic acid in rain. The acid rain dissolves rocks releasing minerals, such as calcium and sodium ions, which enter waterways and eventually end up in oceans. Dead organisms sink to the ocean floor and along with mineral ions become ocean sediment. Over time, heat and pressure turn the sediment into rock, storing the carbon. To complete the cycle, the stored carbon can be returned to the atmosphere through volcanic activity.

In the fast cycle, atmospheric CO$_2$ is converted into organic matter by photoautotrophs, such as plants and algae, through the process of photosynthesis. During photosynthesis carbon atoms from CO$_2$ are fixed into glucose, which provides the energy and carbon skeletons for the synthesis of all other organic compounds in the autotroph. The carbon within organic matter can be returned to the atmosphere in four ways: a) through respiration when a plant utilizes sugars for growth and maintenance; b) the organic matter is consumed by animals, which derive energy from it through respiration; c) organic matter decays through microbial activity; or d) the organic matter is combusted [NASA, 2011].

An illustration of the fluxes and sinks in the carbon cycle between the atmosphere, land, and ocean is shown in Figure 3. Carbon sinks (pools) are reservoirs where carbon accumulates and is stored for an indefinite period of time. In the image the yellow text indicates carbon contribution from natural sources and the white text indicates carbon sinks, while the red text indicates carbon contributions from human activity. Terrestrial ecosystems and oceans absorb a portion of the human emissions (i.e., 3 and 2 Pg C/yr, respectively; a Pg equals 10$^{15}$g or 10$^{12}$ kg); however, there is still a net annual increase of atmospheric carbon (4 Pg C/yr). The atmosphere contains a stock of around 800 Pg C. The oceans account for 38,000 Pg C, with 1,000 Pg C in surface waters and 37,000 Pg C in deep oceans. Through photosynthesis, respiration, and decomposition, surface water and deep oceans fluctuate by 2 Pg C. The buildup of dissolved rocks and organic matter, or reactive sediments, at the bottom of the oceans holds 6,000 Pg C. For terrestrial carbon, the biotic sink (plant biomass) contains 550 Pg C, which is accumulated through the photosynthetic sequestration of 120 Pg C from the atmosphere. As a result of respiration, vegetation returns 60 Pg of the sequestered carbon back to the atmosphere. The organic matter in the soil contains around 2,300 Pg C. Terrestrial geologic formations are a sink to approximately 10,000 Pg C. The natural carbon cycle is then influenced by anthropogenic emissions, such as fossil-fuel combustion and land-use change, which contribute 9 Pg C/yr in emissions to the atmosphere.
Figure 3. The carbon cycle in Pg C/yr [U.S. DOE, 2008]

Anthropogenic activities such as the combustion of fossil fuels, deforestation, wildfires, land-use conversion, and agricultural practices have disrupted the balance of the natural carbon cycle [Grace, 2004] and led to a rapid increase in atmospheric CO$_2$ concentrations. The burning of fossil fuels releases carbon sequestered in the slow cycle, which took millions of years to store, back into the atmosphere at rates that disrupt the carbon balance. Thus, the carbon stored in the slow cycle now becomes part of the fast cycle.

This migration of CO$_2$ from the slow to the fast cycle has implications for global climate change due to CO$_2$’s ability to absorb electromagnetic radiation from the sun or earth and re-emit or reflect electromagnetic radiation back to the earth, clouds, and the atmosphere itself. The main characteristics that determine the effects of CO$_2$ as a GHG are how well the CO$_2$ absorbs energy and how long the CO$_2$ molecule remains in the atmosphere [IPCC, 2007]. These two characteristics determine the measure of the total energy a GHG absorbs over a certain period of time, or the Global Warming Potential (GWP); the larger the GWP, the greater the impact of a GHG. The GWP of CO$_2$ is 1 for a period of 100 years, where the CO$_2$ GWP serves as the baseline for comparing other GHGs (CO$_2$-Eq equals the mass of GHG multiplied by GWP). For example, nitrous oxide (N$_2$O) has a GWP of 298, which means one gram of N$_2$O, has the same GWP as 298 grams of CO$_2$ [NRC, 2010]. Table 2 shows the two characteristics used to determine GWP: lifetime and radiative efficiency with the GWPs for CO$_2$, methane (CH$_4$), and N$_2$O. The low baseline rating for CO$_2$ means that it has a low potential as a GHG; however, it is one of the most abundant gases in the atmosphere and is released in the highest amounts.
Table 2. Radiative efficiency and GWPs for several GHGs [IPCC, 2007]

<table>
<thead>
<tr>
<th>Name and Formula</th>
<th>Radiative Efficiency (W/m² ppb)</th>
<th>GWP for Given Time Horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20 yr</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>1.4 x 10⁻⁵</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>3.7 x 10⁻⁴</td>
<td>72</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O)</td>
<td>3.03 x 10⁻³</td>
<td>289</td>
</tr>
</tbody>
</table>

Carbon in Biomass vs. Atmospheric CO₂

Atmospheric CO₂ is not directly stored in biomass (living or recently living biological organisms). To be sequestered, plants must fix CO₂ molecules, through photosynthesis into sugars, which are used to synthesize other carbon-containing molecules. These molecules comprise almost the entirety biomass and, according to Woodall et al. [2011], roughly half of a tree’s biomass is composed of roughly 50% carbon atoms. The atomic weight of carbon is 12 atomic mass units (AMU) and the atomic weight of CO₂ is 44 AMU (Equations 1-3). Equation 4 reveals that 3.67 tons of CO₂ is offset by sequestering one ton of carbon.

1 carbon atom (C) = 12 AMU
1 oxygen atom (O) = 16 AMU
1 CO₂ molecule = 1C + 2O = (1x12 + 2x16) = 44 AMU
CO₂ molecule / C molecule = 44/12=3.67

Terrestrial Sequestration

Terrestrial sequestration can be defined as the removal of CO₂ from the atmosphere, or the prevention of CO₂ emissions from ecosystems [U.S. DOE-NETL, 2008]. There are many strategies for terrestrial sequestration, including forest and agricultural land management, restoration of natural ecosystems, afforestation, and reforestation [U.S. DOE-NETL, 2010]. These strategies utilize the natural process of photosynthesis to sequester carbon in living and dead biomass, and soil. Terrestrial sequestration can be a viable carbon storage strategy because of its relatively low costs, ease of installment, and its positive effect on the health of the environment. Terrestrial ecosystems used for sequestration are grouped into three main categories: forests, soils, and wetlands [Lal, 2008]. The soil sink offers the largest opportunity for carbon storage (soil organic carbon, SOC) and for preventing emissions [U.S. DOE, 2008].

In the U.S., land conversion from natural forest ecosystems to agricultural uses and mining, in addition to natural forces (e.g., fire and erosion), have reduced the terrestrial SOC by 20-50% from the land’s original level [U.S. DOE-NETL, 2010]. Utilizing land-management practices that create effective and efficient vegetative ecosystems offers an opportunity for increased carbon sequestration into the soil pool. It should be noted that because it is much easier to combust carbon in soil than to replace it, sequestering carbon in soils takes a relatively long time.

A recent National Energy Technology Laboratory report discusses management practices for different land uses [U.S. DOE-NETL, 2010]. It suggests re-vegetating mined lands, which have low SOC, as well as implementing forest-management practices that affect logging and burning of forest ecosystems. These management strategies can result in increasing soil carbon sequestration rates; however, it can take many years for these processes to raise the SOC...
significantly. Grasslands and rangelands used for grazing can also be managed to increase carbon sequestration. Recommended management practices include: rotational and controlled grazing, protecting sensitive ecosystems, and improving cultivation of vegetation. Agricultural lands are influenced by many factors, such as crop type, soil type, weather and climatic conditions, and planting and harvesting processes. Recommended best practices (RBPs) for agricultural land management include conservation tillage (e.g., no- and low-till practices increase SOC), reduction of chemicals usage, and crop residue retention.

A study conducted by the Midwest Regional Carbon Sequestration Partnership (MRCSP) [2011], which included seven states (i.e., Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia), states that terrestrial sequestration has the potential to sequester 15% of the regional point-source CO\(_2\) emissions. Table 3 shows data from a report by Lal et al. [2003] that demonstrates the potential for the soil carbon storage if RBPs were used on all land. The study concluded that the biggest potential for soil-carbon storage comes from croplands and forestlands; however, the storage potential has a high degree of variability.

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Carbon Storage Potential (Mt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cropland</td>
<td>45-98</td>
</tr>
<tr>
<td>Grazing Land</td>
<td>13-70</td>
</tr>
<tr>
<td>Forestland</td>
<td>25-102</td>
</tr>
<tr>
<td>Land conversion</td>
<td>21-77</td>
</tr>
<tr>
<td>Land restoration</td>
<td>25-60</td>
</tr>
<tr>
<td>Other</td>
<td>15-25</td>
</tr>
<tr>
<td>Total</td>
<td>144-432</td>
</tr>
</tbody>
</table>

As with Lal et al. [2008], this report looks at terrestrial land uses for carbon stored by agricultural crops, hardwoods, and perennial grasses. Agricultural crops, hardwood trees, and dedicated energy crops, such as switchgrass (*Panicum virgatum* L.), *Miscanthus (Miscanthus giganteus*) L., or woody crops (hybrid poplars (*Populus* spp.)), all share a common carbon sequestration process. The difference between their sequestration potentials is determined by their life cycles and human intervention. Agricultural crops (for purposes of this report, corn and soybean) need to be planted and harvested annually. These planting and harvesting processes require extensive energy and material inputs. In addition, forests require a management system to keep the forest growing at its maximum potential, which may include controlled burns and forest thinning. Although dedicated energy crops require management and harvesting, some do not require annual cultivation.

### 1.2 Fossil Fuel and Electricity Generation

According to the EPA [2014a], there are five main sectors of fossil fuel-related CO\(_2\) emissions: electricity generation, transportation, industrial, residential, and commercial. Of the total CO\(_2\) emissions per year, non-fossil fuel combustion accounts for only 6%. Figure 4 includes data on U.S. CO\(_2\) emissions by source, and shows that electricity generation accounted for 38% of the total in 2012. Additionally, Figure 5 depicts CO\(_2\) emissions by fuel type and end use. It shows that petroleum, coal, and natural gas are the largest sources of CO\(_2\) emissions, contributing 2.3
billion tons (43%), 1.7 billion tons (31%), and 1.4 billion tons (26%), respectively, in 2012 [U.S. EIA, 2013].

Figure 4. U.S. CO₂ emissions by source [U.S. EPA, 2014e]

Figure 5. 2012 U.S. fossil fuel CO₂ combustion emissions by sector/fuel [U.S. EPA, 2014d]

Worldwide electricity generation is heavily dependent on fossil fuels, such as petroleum, natural gas, and coal, all of which are considered non-renewable resources. Power plants combust the fossil fuels to generate heat, to create steam, to drive turbines. Combustion of fossil fuels generates flue gases that contain GHGs and metals [Duke Energy, 2014]. Fossil-fuel-fired power plants are the main source of electricity in the U.S., accounting for 68% of the nation’s electricity in 2012, with 39% generated from coal-fired plants [U.S. EIA, 2014f]. In 2012, 81% of electricity in Indiana was generated using coal; 13% generated using natural gas; and hydroelectric, petroleum, wind contributing the remainder [U.S. EIA, 2014f]. Figure 6 shows the distribution of electricity to end-uses in 2012. Residential and commercial electricity usage accounted for 33% of total consumption, much of which is for lighting and appliances. It should be noted that the 29% GHG emissions for the transportation sector includes the combustion of fossil fuels (e.g., passenger cars, trucks, and planes) and has a small proportion from electricity (e.g., monorail or electric vehicles).
The electric power sector is the largest contributor to total U.S. GHG emissions, accounting for 32% in 2012, with CO₂ accounting for 84% of the total GHG. Within the three major fuel types (i.e., coal, natural gas, and petroleum) used by the electric-power sector, coal was used to generate 39% of U.S. electricity and contributed 75% of the emissions, or 1,511 Tg CO₂-Eq (1 Tg is equal to 106 tons) in 2012. By way of comparison, in 2012 natural gas was used to generate 29% of U.S. electricity, but only emitted 492 Tg CO₂-Eq, whereas petroleum generated 1% of electricity and emitted 19 Tg CO₂-Eq [U.S. EPA, 2014]. Table 4 shows data from the U.S. EPA’s “Inventory of U.S. Greenhouse Gas Emissions and Sinks” for the years 1990 to 2012. Large amounts of CO₂ have consistently come from coal combustion, with coal emissions at least three times those of natural gas for the years shown. However, electricity produced from coal only led to 8% more electricity generation than natural gas.

Currently, many states are highly dependent on the use of coal to generate electricity. Texas, Indiana, Illinois, Missouri, Pennsylvania, Ohio, and Kentucky all consumed over 40,000,000 T (1 short ton (T) is equal to 2,000 lbs or 907.185 kg) of coal for electricity generation in 2012 [NMA, 2013]. These were also among the top 11 states for coal production. Figure 7 shows the net electricity generation by state in the U.S. for nine of the top 10 highest coal-consuming states, with Mississippi included for comparison, as it is one of the lower coal-consuming states. In addition to being among the top 10 coal-consuming states, Indiana is among the top 10 coal-producing states in the nation, providing 3.5% of total U.S coal [NMA, 2013]. In 2012, Indiana consumed 54,571,000 T of coal [NMA, 2013], which was second only to Texas, where 99,000,000 T were consumed.

### Table 4. Electricity generation-related CO₂ emissions (Tg CO₂-Eq.) [U.S. EPA, 2014d]

<table>
<thead>
<tr>
<th>Fuel Type or Source</th>
<th>1990</th>
<th>2005</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Fuel Combustion</td>
<td>1,821</td>
<td>2,402</td>
<td>2,361</td>
<td>2,146</td>
<td>2,259</td>
<td>2,159</td>
<td>2,023</td>
</tr>
<tr>
<td>Coal</td>
<td>1,548</td>
<td>1,939</td>
<td>1,959</td>
<td>1,741</td>
<td>1,828</td>
<td>1,723</td>
<td>1,511</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>175</td>
<td>319</td>
<td>362</td>
<td>372</td>
<td>399</td>
<td>409</td>
<td>492</td>
</tr>
<tr>
<td>Petroleum</td>
<td>98</td>
<td>99</td>
<td>39</td>
<td>33</td>
<td>32</td>
<td>27</td>
<td>19</td>
</tr>
<tr>
<td>Incineration of Waste</td>
<td>8</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Other Carbonates Process Uses</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Total CO₂</td>
<td>1,831</td>
<td>2,418</td>
<td>2,376</td>
<td>2,162</td>
<td>2,276</td>
<td>2,175</td>
<td>2,039</td>
</tr>
</tbody>
</table>
**CO₂ Emission Sources**

Carbon dioxide emissions, largely from anthropogenic activities, accounted for 82% (6,526 Tg) of total U.S. GHG emissions in 2012 (Figure 8). CO₂ emissions are over nine times greater than CH₄ emissions and over 13 times greater than N₂O emissions. Figure 9 shows GHG emission data for 1990 to 2012 by percentage of total Tg CO₂ Eq and demonstrates that CO₂ is the major GHG emission for the U.S. The slight decline in CO₂ emissions from 2007 to 2012 can be attributed to an economic downturn.

**Figure 7.** 2012 electricity net generation by source for 9 of the top 10 coal consuming states, with a lower coal consuming state adapted from data from U.S. EIA [2014a]

**Figure 8.** U.S. GHG emissions (Tg CO₂-Eq) in 2012 [U.S. EPA, 2014e]
Because the purpose of this report is to evaluate terrestrial sequestration strategies to offset fossil-fuel electricity generation, transportation, and other emission sources will not be evaluated. The remainder of this report will describe three biomass strategies for sequestering CO₂ in Indiana. Specifically, Section 2 will detail the potential of hardwood trees for carbon sequestration and storage; Section 3 will look at agricultural crops and their residues for potential sequestering of carbon; and Section 4 will evaluate the potential of dedicated energy crops for carbon sequestration.

2.0 Forestry Measures for CO₂ Utilization

There are several biological, physical, and chemical processes by which carbon can be sequestered (e.g., forestry and agriculture, ocean fertilization, geological injection, and chemical scrubbing) [Yang, 2008]. However, the focus of this section is on the potential for carbon sequestration through forest management. In particular, the role that hardwood trees play in the sequestration of carbon will be described. In this regard, only the CO₂ released from natural and anthropogenic sources will be considered. According to Lundmark et al. [2014], a sustainably managed forest can contribute to a reduction of CO₂ emissions to the atmosphere by acting as a carbon sink, increasing carbon storage in wood products and using wood as a substitute for products that result in higher emissions. The importance of trees cannot be understated, as they help provide fresh air, shade, material for various industrial processes, and aesthetic beauty, among many other benefits. Hickory, maple, oak, and walnut hardwoods are valuable and native to Indiana; therefore, they will be the focus of this report. With the increasing usage of metals and plastics, the role of wood in our lives has decreased; however, the utilization of wood products remains significant.
2.1 Overview of Carbon Cycle for Hardwoods

Each geographic region has a characteristic forest-tree community. Although there are similarities between the different regions and ecosystems, forest types in characteristic of a locale should be investigated independently. Biomass from living trees with a diameter at breast height (dbh; 1.37 m (4.5 ft) above ground level on the uphill side of the tree) of 2.5 cm (1 in) is often the focus of many studies, because this is the size for which data exists. However, this can lead to bias and even counter-productive recommendations. Biomass includes coarse roots, stems, branches, and foliage [Smith et al., 2004]. It should be noted that other carbon storage models account for litter, dead wood, and often soils for a more accurate analysis of carbon storage. Photoautotrophic organisms, such as hardwood trees, absorb CO₂ from the atmosphere as depicted in Figure 10.

![Carbon cycle for a single tree](image)

Figure 10. Carbon cycle for a single tree [Martin, 2013]¹

Through the process of photosynthesis, the carbon atoms from the CO₂ molecule are incorporated into sugars in a sub-cellular organelle known as the chloroplast. These sugars provide the energy and carbon skeletons needed for growth. Following germination, seedling photosynthetic rates are relatively linear and are dictated by climatic conditions, resource availability, and the genetic make-up of the individual. At the end of the temperate zone’s growing season, deciduous trees shed their leaves. The fallen leaves will decompose, releasing the captured CO₂ back into the atmosphere. Growth resumes in the spring after the leaves have been replenished. Growth rates increase with leaf area, which defines the tree’s photosynthetic capacity. A portion of the fixed carbon is used up in maintenance respiration and released back

¹ Adapted from Martin [2013]
² Reprinted with permission from Ross-Davis et al. [2005]; copyright by the Society of American
to the atmosphere as CO₂ [Srivastava, 2010]; the rest remains in the standing biomass. Carbon in standing biomass can flow through the carbon cycle in a number of ways. For example, CO₂ is released when biomass is consumed and respired or excreted by other living organisms, including microbes, involved in decomposition.

**Growth Cycle, Carbon Uptake, and Carbon Sequestration**

The Kyoto Protocol, an international agreement among developed countries to reduce GHG emissions, suggested three ways to approach sequestration of carbon pools: afforestation, reforestation, and additionality. Afforestation refers to the planting of trees where there were none before (e.g., grasslands or re-purposed farm land) [Smith, 2002]. Reforestation refers to the replanting of trees on harvested forestland. Additionality refers to the positive difference in sequestration rate achieved through forest-management practices and is applicable to both afforestation and reforestation [Valatin, 2011]. In the three different sequestration scenarios, the processes associated with the manufacturing of wood products may also be considered, where the wood products do not emit carbon immediately, unless they are combusted as fuel.

The three primary factors that have bearing on the amount of additional carbon sequestered in tree forests are: the effect of land-use change on standing biomass, the effect of changes in silviculture on biomass retained after a harvest, and the effect of the conversion of raw materials to long-lived wood products. For managed forests, planting typically takes place in late winter or early spring, after the ground has thawed [Pijut, 2003]. Over time, the trees grow and sequester more carbon. As trees in Indiana and states with similar climates are dormant during the winter, hardwoods in regions with longer growing seasons (e.g., the Southeastern U.S.) have the potential to sequester greater amounts of carbon.

Indiana lies on the eastern edge of what is known as the northern prairie states region (Figure 11), which includes Illinois, Iowa, Missouri, Kansas, Nebraska, and South and North Dakota. However, the northern part of the state is close to the lake states of Michigan, Wisconsin, and Minnesota. The eastern part of the state borders the northeast physiographic region, which encompasses states from Ohio to Maine, including West Virginia. Finally, the southern part of the state is bordered by the south-central region, which includes Kentucky, Tennessee, Alabama, Louisiana, Mississippi, Arkansas, Oklahoma, and Texas [Smith et al., 2006].

![Figure 11. Forest regions of the U.S. [Smith et al., 2006]](image-url)
There have been various reports regarding hardwoods in the state of Indiana; however, given its proximity to different forest regions, this report will also include information pertaining to nearby states with similar geographies. These include Illinois, Michigan, Ohio, Kentucky, and Missouri, because they are most similar. Spille et al. [2012] described the carbon-storage potential for oak, hickory, birch, and maple trees in Indiana. Their study, which derived information from the report “How to estimate forest carbon for large areas from inventory data” by Smith et al. [2004], included data on the growth cycle of trees around the state and provides a calculator for assessing an individual person’s carbon footprint. Litynski et al. [2006] examined the use of terrestrial ecosystems to sequester CO₂ where hardwoods will play a pivotal role and discussed various research efforts to establish hardwoods on abandoned mining sites. Woodall et al. [2011] examined the inventory of trees in Indiana, focusing on the top 12 tree species by total number of trees for the state (Figure 12). It should be noted that there are softwood trees (e.g., eastern redcedar) are present within Indiana’s top species.

![Figure 12. Tree diversity in Indiana [Woodall et al., 2011]](image)

Residues, Thinnings, and Harvested Materials

A system of classifying forest ecosystem carbon components was presented by Smith et al. [2006] and is summarized in Table 5. For example, standing dead trees contain carbon in the form of coarse roots, stems, and branches. Also, there is biomass in the understory vegetation that should be considered. Dead wood, or coarse woody debris, includes stumps, coarse roots of stumps, tops, branches or any parts shed by trees, and logging residue. Organic material on the forest floor includes fine woody debris, tree litter, and humus.

Carbon is sequestered by trees in woody biomass (e.g., branches, stems, and coarse roots) and non-woody biomass (e.g., foliage, fine roots, and reproductive tissues). Non-woody biomass is often unaccounted for in calculations because they are inconsequential, with mass values within the margin of error of estimates. However, non-woody material from hardwoods cannot be gathered in a cost-effective manner. Harvesting intensity affects the amount of material left behind. Eventually, organic matter in the soil decomposes; the rate at which this occurs varies by climate, biomass type, and the soil microfauna involved in decomposition. Furthermore, studies have shown that harvesting has little or no effect on SOC [Peckham and Gower, 2011].
Table 5. Carbon pools related to trees [Smith et al., 2006]

<table>
<thead>
<tr>
<th>Forest Ecosystem Carbon Pools</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live trees</td>
<td>Live trees with dbh of at least 2.5 cm (1 in), including mass of coarse roots, stems, branches, and foliage.</td>
</tr>
<tr>
<td>Standing dead trees</td>
<td>Standing dead trees with dbh of at least 2.5 cm, including carbon mass of coarse roots, stems, and branches.</td>
</tr>
<tr>
<td>Understory vegetation</td>
<td>Live vegetation that includes the roots, stems, branches, foliage of seedlings (trees less than 2.5 cm dbh), shrubs, and bushes.</td>
</tr>
<tr>
<td>Down dead wood</td>
<td>Material including logging residue and coarse dead wood on ground larger than 7.5 cm (3 in) in diameter, stumps, and coarse roots of stumps.</td>
</tr>
<tr>
<td>Forest floor</td>
<td>Forest floor organic material including fine woody debris 7.5 cm in diameter, tree litter, humus, and fine roots in the layer above mineral soil.</td>
</tr>
<tr>
<td>Soil organic carbon</td>
<td>Below-ground carbon without coarse roots, but including fine roots and other organic carbon not in other pools, to a depth of 1 m (3.3 ft).</td>
</tr>
</tbody>
</table>

2.2 Land Issues and Yields

Two hundred years ago, 85% of Indiana was forested; today that area is approximately 20%, with 96% of the tree species being hardwoods [Bratkovich et al., 2004]. The potential for utilizing Indiana’s lands for planting of hardwoods is affected by a wide range of variables. The feasibility for implementation will be briefly mentioned, because the conversion of land for this purpose is considerable, but the issue is highly complex. Afforestation relates to the use of forests as a terrestrial carbon sink; therefore, it is appropriate to evaluate whether the commercial use of forests contributes significantly to pools of sequestered carbon.

Land Availability

The land available for the utilization of hardwoods for carbon sequestration depends on many factors. Most importantly, it is not practical to replace agricultural crops with hardwoods, because the former provide a greater annual net income to landowners and their displacement would have many economic ramifications. Therefore, lands that would be suitable for growing hardwoods need to be identified. Indiana’s area (including land and water) is 9,278,900 ha (22,928,756 ac). Of this land area, 5,957,100 ha (14,720,396 ac) are being used as farmland and 5,095,200 ha (12,590,633 ac) are dedicated to croplands [USDA, 2014a]. Farmland includes roads and homes, whereas cropland does not. According to Dale [2014], for the year 2013, Indiana had approximately 1,980,000 ha (4,900,000 ac) of forests, a 2.8% increase from 2008 (studies performed at five-year intervals) (Gormanson, 2014). There is a difference between forestland and forests, where the former may or may not have any trees. The non-forested part of forestland can be important, because it is generally available for reforestation. Indiana’s forestland acreage increased by approximately 15,022 ha/yr (37,120 ac/yr) from 1998 to 2009.

Table 6 shows Indiana’s forestland ownership for the year 2009 and the change since 1998. The table is divided into four ownership groups: federal, state, county or municipality, and family or private. It is clear that family or private ownership accounts for the largest percentage of
forestland. For this reason, cooperation with private landowners is crucial for implementation of a hardwood sequestration project.

Table 6. Indiana forestland ownership by percentage in 2009 [Hoover and Settle, 2010]

<table>
<thead>
<tr>
<th>Year</th>
<th>Federal</th>
<th>State</th>
<th>County/Municipality</th>
<th>Family/Private</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>8.0</td>
<td>7.3</td>
<td>0.7</td>
<td>84.1</td>
</tr>
<tr>
<td>2006</td>
<td>8.3</td>
<td>5.4</td>
<td>0.7</td>
<td>85.7</td>
</tr>
<tr>
<td>2003</td>
<td>9.2</td>
<td>4.5</td>
<td>0.6</td>
<td>85.7</td>
</tr>
<tr>
<td>1998</td>
<td>8.6</td>
<td>5.5</td>
<td>0.3</td>
<td>85.6</td>
</tr>
</tbody>
</table>

Shaver [2014] stated that, to date, approximately 263,045 ha (650,000 ac) of Indiana forests have been enrolled in the Classified Forests and Wildlands Program by the Indiana Department of Natural Resources (IDNR). This program provides a tax incentive to private landowners who keep their land forested. According to the IDNR Division of Forestry [2014], to qualify for the program, the enrolled area must be at least 4.05 continuous ha (10 ac) and the owner must be a good steward of the land (e.g., no grazing livestock, building of structures, or intentional burning). Tree plantations with at least 400 timber-producing trees per acre may also be eligible for the program. For its part, the state of Indiana reduces the taxable value of the land to $1.

According to Ross-Davis et al. [2005], some landowners in Indiana have been planting hardwoods for conservation-related reasons. Figure 13 shows the results of a survey in which landowners placed a higher value on conservation or aesthetics than financial gain. Nevertheless, some creative thinking may be needed to identify adequate land. For example, there is the possibility of planting hardwoods for carbon sequestration around businesses, along city streets, and in other public places. Furthermore, consideration should be given to planting hardwoods as shelterbelts, windbreaks, and in riparian zones.

Rehabilitation of Marginal Lands

Lands where hardwoods do not interfere with other industrial applications are ideal. Marginal land, which is poorly suited for growing agricultural crops [Gelfand, 2013], may be appropriate for growing hardwoods. Marginal agricultural lands are defined as land that is not economically viable for crop production [Strijker, 2005]. Other definitions of marginal lands include contaminated lands or lands with erosion, flooding, and poor drainage, along with having steep slopes [Gopalakrishnan et al., 2011]. In addition, marginal lands often have soils with a history of industrial, military, or mining activities [Taghavi et al., 2008]. Marginal agriculture lands may be inadequate for crops, but can be excellent for trees, while lands after mining activities are poor but tolerable for trees. A key feature of planting hardwoods is that the need for periodic maintenance throughout their life may be minimal. However, if the maximum potential growth or targeting specific wood properties and dimensions is the main objective, then maintenance may be needed and economically justified.

Pre-commercial thinning, or competing vegetation control operations, are perhaps necessary. Pre-commercial thinning involves removing some trees in over-stocked stands to prevent growth stagnation (small live-crown ratios, small diameters, and low volume per acre) and increases the growth of the remaining trees. This could be implemented as early as 3-4 years after planting depending on the rotation length, but additional gains can be achieved when older hardwood
stands are thinned [Williams, 2012]. Depending on the size of the trees at the timing, the thinning may be commercial rather than pre-commercial. Ultimately, this depends on whether the harvested material is suitable for sale. Marginal lands for crops are usually less productive for trees and, thus, thinning is less profitable even if growing large lumber-producing trees is the objective. If sequestration is the objective, though, pre-commercial thinning will likely not be employed unless, through some optimization process, the longevity of wood products (e.g., furniture) compensates for the lost growth on the thinned trees (which decompose to the atmosphere) and the fossil fuel-derived CO$_2$ released by thinning equipment.

Figure 13. Reasons landowners provide for planting$^2$

The Bear Run mine in Sullivan County, Indiana (Figure 14) is the largest surface mine east of the Mississippi River. According to Peabody Energy [2013], the mine yielded 7,439,000 ton (8,200,000 T) of coal in 2013. The Surface Mining Control and Reclamation Act (SMCRA) requires that coal operators reclaim the overburden from their mining sites [Harper, 2011]. This is an example of a site that will have to be rehabilitated after the mine is decommissioned. According to Litynski et al. [2006], abandoned mined lands often contain little vegetation, wildlife habitat, or benefit to the local economy. These lands can be utilized for planting of hardwoods, where the potential commercial timber production is attractive. About 1 million trees are planted on mine reclamation sites in Indiana each year, which is roughly 20% of the total state nursery production [Jacobs, 2006].

$^2$Reprinted with permission from Ross-Davis et al. [2005]; copyright by the Society of American Foresters
Brownfield sites also provide an opportunity for planting hardwoods. These are lands previously used for industrial or commercial applications [U.S. EPA, 2012]. Urban brownfield sites are not ideal for planting the hardwoods being considered here, given their larger area needs, in comparison to other options (e.g., poplars). However, if the goal of planting hardwoods is to establish a park, then hardwoods are a good option. Zagofsky [2012] describes a project in Lehigh County, Pennsylvania, that transformed a former hazardous-waste site into a meadow park. The property, located beside the Lehigh River, was initially cleared of the contaminated soil. Five hundred and twenty trees were planted on the site using donations made by community members. Although this is a small-scale project and their goal is not to sequester carbon, it illustrates what can be done with hardwoods.

**Planting Density**

There are many reports recommending spacing for tree planting. The crowns of the hardwood trees are larger in diameter than that of many other tree species (e.g., softwoods); therefore, the area they require for growth is greater. In the wild, the number of plants per unit area varies, depending on the site characteristics and species. For example, Roberts and Beinke [1995] state that walnut tree densities can vary from 350 to 1,240 tree/ha (140 to 500 tree/ac) depending on the genotype, site conditions, competing species and age. The desired size of the tree at harvest depends on the intended end use (e.g., peeler logs for slicing veneer, saw logs for cutting dimensional lumber, and trees chipped and pulped for paper production). Planting density decisions may involve a tradeoff between greater cost for higher density and higher risk of failure or loss of future value with a lower density.

It should be noted that every stand in the world undergoes self-competition as their canopies close. Soil, water, and nutrient availability set a maximum limit for leaf area, which determines biomass production and storage. Natural “self-thinning” can be avoided with the commercial thinning, as described previously. Competition reaches a certain level determined by density and average tree size. Biomass accumulation will be higher in more densely planted stands initially, but, ultimately, variables such as soil resources and shade tolerance will determine the amount of biomass produced.

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3 Reprinted with permission from Blair [2010]; credit to BlairPhotoEVV
Planting plans for hardwoods are often developed assuming 70% seedling survival [Davis et al., 2010]. It is clear from Table 7 how important spacing is for the planting of hardwoods, especially if the objective is for a large number of seedlings to survive. For example, a difference of three feet of spacing between hardwoods has a large impact on the number of surviving trees. Given the change in tree density and the carrying capacity of the land, when going from 2.1 m x 2.1 m (7’ x 7’) spacing to 3.0 m x 3.0 m (10’ x 10’) spacing, with 70% survival, over double the amount of carbon can potentially be sequestered initially, but over time tree survival will decline because of competition and reasons given previously. Furthermore, survival hinges on many factors, such as soil conditions, planting practices, planting stock condition, deer herbivory, etc.

<table>
<thead>
<tr>
<th>Spacing-m (ft)</th>
<th>Trees Planted-ha (ac)</th>
<th>Trees per ha (ac) at 70% survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 x 2.1   (7 x 7)</td>
<td>2,197 (889)</td>
<td>1,538 (622)</td>
</tr>
<tr>
<td>2.1 x 2.4   (7 x 8)</td>
<td>1,922 (778)</td>
<td>1,346 (544)</td>
</tr>
<tr>
<td>2.4 x 2.4   (8 x 8)</td>
<td>1,683 (681)</td>
<td>1,178 (476)</td>
</tr>
<tr>
<td>2.4 x 2.7   (8 x 9)</td>
<td>1,495 (605)</td>
<td>1,046 (423)</td>
</tr>
<tr>
<td>2.7 x 2.7   (9 x 9)</td>
<td>1,329 (538)</td>
<td>931 (376)</td>
</tr>
<tr>
<td>2.7 x 3.0   (9 x 10)</td>
<td>1,196 (484)</td>
<td>837 (338)</td>
</tr>
<tr>
<td>3.0 x 3.0   (10 x 10)</td>
<td>1,077 (436)</td>
<td>754 (305)</td>
</tr>
</tbody>
</table>

Tree plantations established in Minnesota for the manufacture of paper and lumber are typically planted at 360-1,680 tree/ha (145-680 tree/ac) [Volk et al., 2010]. It is estimated that in a naturally regenerated maple-beech-birch and oak-hickory forest types in Indiana, there are 370 tree/ha (150 trees/ac) [Smith et al., 2006]. This planting density is likely for a mature stand that began with a much higher density of trees, but the weaker, suppressed trees died through self-thinning. The authors assume that the trees will be allowed to grow for their full life expectancy. However, Indiana state forestry officials feel that the appropriate planting density for hardwoods is 1,980 tree/ha (800 tree/ac); assuming a survival rate of 80%, 1,580 tree/ha (640 tree/ac) would remain. Intermediate treatments (e.g., pre-commercial thinning) may be applied to maintain maximum growth; however, pre-commercial thinning is expensive, so may be avoided if not economically justified. In addition, deer browsing strongly limits regeneration [Rooney and Waller, 2003]. Ultimately, the end-use for the wood derived from the plantation will dictate the density at which the trees should be grown.

End Use: Dimensional Lumber, Peeler Logs, Combustible Fuel

End-use products are those that have not been discarded or destroyed and can include building materials, furniture, wooden containers, pallets, and paper products [Hoover and Settle, 2010]. For wood products, in general the bole of the tree from where it is cut on the stump up to a minimum diameter at the top (e.g., 10 cm (4 in)) is used for manufacturing, with smaller diameters being used for items such as wood pellets or engineered products; all other tree parts are left on the forest floor. A reduction in GHG emissions can be achieved by using wood products that replace more energy-intensive products that are used for the same purpose [Miner et al., 2014]. Typically, products are classified as long- and short-term carbon pool products. According to Perez-Garcia et al. [2005], long-term products, such as lumber, become the basis for substitution of fossil fuel-intensive products and short-term products, such as chips and
sawdust, are used to displace fossil fuels via bio-fuels. Table 8 lists examples of the average service life for wood products.

Hardwood lumber is also used in the furniture-making industry. There is an established market for hardwood furniture and Indiana is one of the top manufacturers of wooden office furniture [Bratkovich et al., 2004]. As wood availability increases, its cost is likely to go down (via the usual relationship between supply and demand), thus increasing manufacturer profitability. Hardwoods can be used for any number of outdoor applications including playgrounds, sheds, playhouses, etc.; however, softwood lumber is typically used. Wood products also decay over time and release carbon back to the atmosphere, completing the carbon cycle; however, this can occur at a slow rate for many products. For example, the end uses of wood in new residential construction can be sequestered from 24 (mobile homes) to 100 years (single-family dwellings) and furniture having the potential for 60 years [Skog, 2000]. Figure 15 depicts a timber cycle for the hardwood industry. The figure lists three stages (i.e., regrow, manufacture, and end of life) for hardwoods and how they are related to the carbon cycle. While this is a simplified version of the carbon cycle for hardwoods, it clearly demonstrates their potential for carbon sequestration.

**Table 8. Example average service life of wood products [Lundmark et al., 2014]**

<table>
<thead>
<tr>
<th>Description</th>
<th>Average service life (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In country</td>
<td></td>
</tr>
<tr>
<td>Building construction</td>
<td>80</td>
</tr>
<tr>
<td>Interior works including furniture</td>
<td>30</td>
</tr>
<tr>
<td>Other wood products (formwork)</td>
<td>10</td>
</tr>
<tr>
<td>Recovered wood for energy storage time</td>
<td>3</td>
</tr>
<tr>
<td>Energy biomass from forest and industrial residual wood</td>
<td>2</td>
</tr>
<tr>
<td>Abroad</td>
<td></td>
</tr>
<tr>
<td>Imported or exported houses/ furniture</td>
<td>50</td>
</tr>
<tr>
<td>Imported or exported ¾-fabricates</td>
<td>50</td>
</tr>
<tr>
<td>Imported or exported semi-fabricates</td>
<td>50</td>
</tr>
<tr>
<td>Imported or exported round wood</td>
<td>30</td>
</tr>
<tr>
<td>Imported or exported residual wood</td>
<td>10</td>
</tr>
<tr>
<td>Exported recovered wood</td>
<td>25</td>
</tr>
<tr>
<td>Recovered post-consumer wood as waste wood for energy purposes</td>
<td>3</td>
</tr>
<tr>
<td>Industrial residual wood resulting abroad from pre-processing of products</td>
<td>2</td>
</tr>
<tr>
<td>Imported/exported industrial residual wood resulting from more processing</td>
<td>2</td>
</tr>
</tbody>
</table>

Additionally, substitution of steel by wood is a possibility with hardwoods in the form of dimensional lumber (e.g., steel fencing versus wood fencing). Again, the storing of carbon in hardwoods can have a benefit to the atmosphere and the economy, where fossil-fuel carbon substitution implies using wood instead of products such as steel or plastics. According to vanKooten [2012], steel consumes fossil fuels during manufacturing; thus, substitution will lead to further reductions in the use of fossil fuels and the release of CO₂ into the atmosphere. However, it should be noted that GHG emissions from the transportation of wood products and raw wood fiber contributes to its carbon footprint.
Hardwood CO₂ Sequestration Potential in Response to EPA Policy Changes

Discarded wood and paper products are typically placed in landfills and are assumed to degrade at a slow rate, which implies that most carbon is stored long-term. However, standing hardwoods can store carbon for just as long and increase the capacity for storage over time, as well as soil and some forest products as shown in Table 8. The EPA policy changes for reduction in CO₂ emissions to a maximum of 499 kg CO₂/MWh (1,100 lbs CO₂/MWh) for power plants gives rise to opportunities for offsetting a portion of those emissions through various technologies. Tree planting to sequester carbon is one way of achieving this objective. According to Spille et al. [2012], the potential for carbon sequestration per tree is approximately 15 kg of CO₂/yr (33 lbs of CO₂/yr) with 3.6 kg (8 lbs) being carbon for a maple-beech-birch and oak-hickory forest type in Indiana, which amounts to 5,560 kg of CO₂/ha/yr (4,950 lbs of CO₂/ac/yr). For the purposes of comparison, the two forest types were combined and averaged and the growth rates were the average over an 80-year growth cycle, because matures trees have more photosynthetic capacity than seedlings. Furthermore, the paper did not consider incorporating the hardwoods into products, where some portion of carbon the tree fixes would return to the atmosphere, depending on how it is utilized. Nevertheless, the results of this study provide insight into the potential carbon sequestration.

A variety of factors (e.g., available land area, planting methods, management techniques, and cost) affect the potential for carbon sequestration by hardwoods, An example of the carbon sequestration potential is shown in Table 9, assuming a planting density of 1,980 tree/ha (800 tree/ac) and a 80% survival rate (1,580 tree/ha (640 tree/ac)) for a length of 40 years. The cost to produce and transplant hardwood seedlings was estimated at $10 ($3/sapling for land and $7/sapling for growth and planting) for individual hardwoods; however for planting hardwoods

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on a per hectare basis, the cost is likely be closer to $1,656/ha ($670/ac). [J. Seifert, personal communication, September 2014]. This cost would not include overhead, second- and third-year weed control, or maintenance for the site. Other forestry officials gave estimates of $667/ha ($270/ac) at a density of 1,980 tree/ha (800 tree/ac), with first-, second-, and third-year weed control bringing the total to $1,730-$1,980/ha ($700-$800/ac) for trees from the state nursery. While this is a rough estimate (e.g., excludes land and opportunity costs) for using only hardwoods for carbon sequestration, it gives some insight into the cost of implementation.

Table 9. Carbon sequestration potential for hardwoods

| Amount of trees-tree/ha (tree/ac) | 1,480-1,980 (600-800) |
| Amount of trees @ 80% survival rate-tree/ha (tree/ac) | 1,190-1,580 (480-640) |
| Costs-$/ha ($/ac) | 1,656-1,980 (670-800) |
| CO2 absorbed per year-ton•CO2/ha/yr (T•CO2/ac/yr) | 17.0-23.7 (8.0-10.6) |
| CO2 absorbed assuming 40 year growth period-ton•CO2 (T•CO2) | 320-423 (716-948) |
| Costs per ton CO2-$/ton•CO2 ($/T•CO2) | 1.75-2.77 (1.58-2.5) |

2.3 Economic and Policy Implications

Economics may ultimately dictate whether hardwoods should be used for carbon sequestration. Several key considerations are shown in Table 9. In addition, Indiana cropland values recently ranged from $12,387 to $19,037/ha ($5,013 to $7,704/ac), with rent estimates ranging $393 and $514 ($159 and $208, respectively) [Dobbins and Cook, 2012]. Existing forest-management policies (i.e., the Classified Forests and Wildlands Program) are also influential.

Indiana has over 210,400 ha (520,000 ac) of private forest certified by the Forest Stewardship Council (FSC) and an additional 60,700 ha (150,000 ac) are certified by both the FSC and the Sustainable Forestry Initiative (SFI) [Settle, 2010]. This third-party verification indicates that policies used in Indiana work and opens up markets for premium hardwoods. For example, Leadership in Energy and Environmental Design (LEED) is used for the certification of green buildings. To obtain LEED points for Indiana building projects, wood previously had to be imported from other states. Through these programs, Indiana companies can now use locally produced wood.

A possibility for policy change could include the donation or allowance of unused land for planting hardwoods. For businesses, the possibility of using hardwoods for sequestration combined with tax breaks may provide the necessary incentive for adopting this approach. Many policy initiatives are possible, but would require cooperation from Indiana state government officials. This is an area that should be investigated further, but is outside the scope of this report.

Furniture Industry and Other Forest Product Companies

Hardwood carbon sequestration could be financially beneficial to wood-product manufacturers. According to Hoover and Settle [2010], there is $51 of economic impact for every board foot of timber produced in Indiana. Furthermore, landowners were paid $164 million for timber, with every $1 being paid creating $48 of value added (value of shipments minus cost of material, supply, fuel, power, container, and contract work) to the final products. Additionally, Indiana is a leading producer of wood office furniture, manufactured homes, wooden kitchen cabinets, wooden caskets, and hardwood plywood-based products, so the importance of having an
abundant supply of available wood cannot be over-stated. If more wood can be grown and processed locally, then shipping costs of raw materials can be reduced.

Finally, expansion of the forest-products industry could lead to job creation. Utilizing marginal lands can have an even greater impact on a number of people affected. Hall [2010] provides some employment numbers for wood products in Indiana (Table 10). Primary wood producers are defined as firms that harvest, transport, and perform initial processing of the logs. Secondary wood producers are those businesses that add value to wood by drying, planing, cutting, and assembling wood products into finished products or parts. Ancillary producers include businesses that are related to the forestry industry, but are not directly related to the primary or secondary groups.

Table 10. Employment by Indiana manufacturing sectors in 2009 [Hall, 2010]

<table>
<thead>
<tr>
<th>Manufacturing Sector</th>
<th>Number of Establishments</th>
<th>Number of Employees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>276</td>
<td>4,565</td>
</tr>
<tr>
<td>Secondary</td>
<td>794</td>
<td>22,849</td>
</tr>
<tr>
<td>Ancillary</td>
<td>216</td>
<td>7,441</td>
</tr>
</tbody>
</table>

Hoover et al. [2013] discuss the prices and trends of hardwood lumber. Their data were collected by surveying people working in sawmills, in veneer mills, with sawdust, as well as in primary industries, such as logging. A summary of results can be seen in Table 11. The nominal average weighted price for average quality of wood rose 17.5% to $449/1,000 board foot (MBF) from 2012 to 2013. MBF is the volume of one thousand boards that are one foot long, one foot wide and one inch thick.

Table 11. Lumber prices in MBF from the Appalachian Market area [Hoover et al., 2013]

<table>
<thead>
<tr>
<th>Tree Type</th>
<th>Lumber Grade</th>
<th>Jan 2010</th>
<th>Jan 2011</th>
<th>Jan 2012</th>
<th>Jan 2013</th>
<th>Sep 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hickory</td>
<td>FAS+Prem</td>
<td>615</td>
<td>640</td>
<td>670</td>
<td>720</td>
<td>800</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>500</td>
<td>530</td>
<td>560</td>
<td>595</td>
<td>685</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>350</td>
<td>405</td>
<td>415</td>
<td>445</td>
<td>500</td>
</tr>
<tr>
<td>Hard Maple</td>
<td>FAS+Prem</td>
<td>1,080</td>
<td>995</td>
<td>1,050</td>
<td>1,075</td>
<td>1,305</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>655</td>
<td>710</td>
<td>750</td>
<td>790</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>480</td>
<td>535</td>
<td>555</td>
<td>550</td>
<td>685</td>
</tr>
<tr>
<td>Soft Maple</td>
<td>FAS+Prem</td>
<td>880</td>
<td>835</td>
<td>845</td>
<td>940</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>535</td>
<td>595</td>
<td>595</td>
<td>650</td>
<td>710</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>275</td>
<td>320</td>
<td>330</td>
<td>340</td>
<td>360</td>
</tr>
<tr>
<td>White Oak</td>
<td>FAS+Prem</td>
<td>915</td>
<td>1,060</td>
<td>995</td>
<td>1,015</td>
<td>1,070</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>540</td>
<td>625</td>
<td>555</td>
<td>575</td>
<td>705</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>365</td>
<td>500</td>
<td>420</td>
<td>475</td>
<td>630</td>
</tr>
<tr>
<td>Red Oak</td>
<td>FAS+Prem</td>
<td>825</td>
<td>930</td>
<td>830</td>
<td>880</td>
<td>1,045</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>560</td>
<td>615</td>
<td>535</td>
<td>570</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>470</td>
<td>540</td>
<td>430</td>
<td>495</td>
<td>660</td>
</tr>
<tr>
<td>Black Walnut</td>
<td>FAS+Prem</td>
<td>1,800</td>
<td>2,105</td>
<td>2,070</td>
<td>1,795</td>
<td>1,905</td>
</tr>
<tr>
<td></td>
<td>No. 1C</td>
<td>765</td>
<td>1,125</td>
<td>1,075</td>
<td>875</td>
<td>935</td>
</tr>
<tr>
<td></td>
<td>No. 2A</td>
<td>360</td>
<td>740</td>
<td>705</td>
<td>475</td>
<td>530</td>
</tr>
</tbody>
</table>
Summary of CO₂ Benefits Relative to EPA Rule

The reduction of CO₂ emissions by the utility companies will lead to an increase in costs for electricity generation. Ultimately, this will be passed on to the consumers, businesses, and municipalities. Planting hardwoods alone may not be enough to offset the regulatory changes, but it can help to reach the target CO₂ emissions level of 499 kg/CO₂/MWh (1,100 lbs CO₂/MWh) for Indiana’s power plants. However, this depends on many factors and the number of additional acres that can be realistically used to plant hardwoods is beyond the scope of this report. There are already many acres being utilized to grow hardwoods for a variety of applications and programs in Indiana to encourage the planting of hardwoods on privately owned lands. Tax credits for biomass plants, similar to credits for wind and solar technologies, would make economic sense for the utility companies. The reduction of CO₂ emissions by the utility companies will lead to an increase in costs for electricity generation. Ultimately, this will be passed on to the consumers, businesses, and municipalities. Planting hardwoods alone may not be enough to offset the regulatory changes, but it can help to reach the target CO₂ emissions level of 499 kg/CO₂/MWh (1,100 lbs CO₂/MWh) for Indiana’s power plants. However, this depends on many factors and the number of additional acres that can be realistically used to plant hardwoods is beyond the scope of this report. There are already many acres being utilized to grow hardwoods for a variety of applications and programs in Indiana to encourage the planting of hardwoods on privately owned lands. Tax credits for biomass plants, similar to credits for wind and solar technologies, would make economic sense for the utility companies.

3.0 Agricultural Crops and their Residues for Carbon Utilization

Agricultural croplands occupy 16% of the total land area of the U.S., which is equivalent to 159 Mha 393 (Mac) [U.S. EPA, 2014e]. Given the large area and high growth rates, agricultural crops have the potential to significantly influence the global carbon cycle. The use of agricultural crops as a strategy for carbon sequestration has been advocated in the Kyoto Protocol and by the Intergovernmental Panel on Climate Change [IPCC, 2000]. The three areas of agricultural production that can be altered to improve net CO₂ sequestration are: land management practices, crop and residue end use, and soil alterations and amendments. The IPCC Second Assessment Report stated that agricultural soils have the potential to sequester 23 to 44 Gt of C (1 Gt = 10⁹ ton). Increasing levels of SOC has many environmental benefits, including higher crop yields, reduced soil erosion and runoff, and improved water filtration. It is imperative to consider GHG reduction potential of the whole system (i.e., biological plus industrial), because when farmers use energy-intensive amendments (e.g., fertilizer), they amount of net sequestration. This section will describe the role that agricultural crops play in the carbon cycle and their potential for carbon sequestration.

3.1 Overview of Carbon Cycle for Agricultural Crops and Residues

Agricultural crop biomass stores carbon for a short-term, because much of this carbon is returned relatively quickly to the atmosphere through harvest, decay, and digestion (when used as animal feed) [U.S. DOE, 2008]. The remaining carbon the crop fixes moves below ground to the soil carbon source by transfer through the plant’s roots and decomposition by microbial activity. The rate of decomposition depends on the properties of the plant matter itself, the characteristics of the soil, how the soil is managed, and the local climate [USDA, 2007]. The properties of soils will determine the potential concentration of SOC that can be stored; once soils become fully saturated with organic carbon, sequestration ceases. However, most agricultural soils have much unused potential to sequester CO₂.

Lands converted to agricultural use begin to lose SOC as soon as cultivation occurs, especially in the 0.5-1.0 m depth [U.S. DOE, 2008] and occurs rapidly during the first 20-50 years of
cultivation from prior use as forest and grassland [Lal, 2001]. Continued cultivation results in soils containing between 50-80% of the original SOC content [Lal, 2008; Dick et al., 1998]. This depreciation offers a sink for agricultural crops to store their fixed carbon. BMPs offer an opportunity for agricultural crops to replenish lost SOC while reducing atmospheric CO₂. BMPs will vary by the different crop types, land types (including soils), and climates, and includes reducing tillage intensity; prolonging the storage of SOC by slowing the rate of organic matter decomposition; and increasing crop yields, which would lead to increased crop residues left to return to the soil. A basic model of agricultural crop carbon sequestration created by the Center for Carbon Capturing Crops (C2C2) is shown in Figure 16.

Figure 16. Agricultural crops C sequestration model [Schnable, 2014]

Some agricultural-crop biomass is utilized for energy production, such as a feedstock for biofuels, human food, and animal feed. Utilization of biofuel does return CO₂ to the atmosphere, but its carbon footprint is lower than petroleum-based fuels when considering the carbon life cycle. Co-firing (combination of two different fuels, a base and a dissimilar fuel) has the potential to lower the power plant’s emissions, as the carbon released by the biomass was stored during growth. It should be noted that co-firing is less efficient, thermally, than burning pure coal. Agricultural-crop biomass use as a feedstock for energy production will be detailed in the Food vs. Fuel and Biofuel sections below.

Human and animal consumption of agricultural crops utilize various components of biomass (e.g., carbohydrates, lipids, and proteins) for energy carbon skeletons needed to function and accumulate biomass. The fixed carbon in the consumed biomass is transferred from one type of

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5 Reprinted with permission from Patrick Schnable [2014], Iowa State University
short-term storage to another. In the case of animal feed, the second storage of biomass can lead to a third short-term storage through human and predator consumption. There are many factors that affect intermediate storage and to fully evaluate this consumption a life-cycle analysis would need to be performed.

**Types: Corn, Soybeans, and Stover**

The potential for carbon sequestration in agriculture varies by crop. For the purposes of this report, the two largest agricultural crops (by harvested area) produced in the U.S., corn and soybeans, will be evaluated. In 2011, 34 Mha (84 Mac) of corn were harvested and soybeans were grown on 30 Mha (74 Mac) [USDA, 2013a]. Nationally, Indiana was fifth in area for corn (2.3 Mha (5.6 Mac)) and fourth for soybean (2.2 Mha (5.4 Mac)) in 2011. These are Indiana’s two main agricultural crops by acreage harvested and value [USDA, 2014a]. The harvested corn is used for human food, animal feed, and industrial processes. Figure 17 shows data for major corn uses in the U.S. for the years 1980 to 2013 [USDA, 2014b]. Corn is processed in two main ways: wet millers process corn for syrups, glucose and dextrose, starches, oils, alcohols, and ethanol; dry millers process corn into cereal flakes, flour, grits, meal, and brewers grits for beer production [USDA, 2014c].

Corn and soybean production is concentrated in the Heartland region, which includes Illinois, Iowa, Indiana, portions of South Dakota and Nebraska, western Kentucky and Ohio, and the northern two-thirds of Missouri. In the Heartland, cultivation of corn and soybeans is usually done in rotations (i.e., corn and soybean are grown in alternate years). This particular rotation is used to increase yields and reduce the need to control weeds and diseases. For example, soybeans form symbiotic associations with *Rhizobia* bacteria, resulting in root nodules that convert diatomic atmospheric nitrogen (N\(_2\)) to a plant-available form of N. Nitrogen is a critical plant nutrient and its enrichment reduces the need for fertilizer when corn is grown in the subsequent year. Studies by the University of Illinois, Ohio State University, and Purdue University have shown a significant increase in corn yields when the cropping soybean in alternate years [Mannering and Griffith, 1985].

When corn and soybean crops are harvested, the residue left behind, often called “stover”, has traditionally been used for animal foraging, or collected for animal feed, silage, and bedding [Myers and Underwood, 1992]. When stover is left behind, it helps reduce soil erosion, return elements back to the soil, and reduce soil compaction [Alexander, 2014]. Agricultural crop residues have been recently utilized to co-fire electricity generation plants and for liquid biofuel production. When co-fired, residues also serve as a biofuel; energy stored in the biomass is liberated by direct combustion, as opposed to converting constituents in the biomass to a liquid fuel, which is then combusted. Technological and scientific advances that improve the conversion efficiency and expand the types of liquid fuels and by-products produced from these cellulosic feedstocks will increase the demand for crop residues for biofuel production [Ertl, 2013].

**Growth Cycle, Carbon Uptake, and Sequestration**

The essential features of the growth cycles of both corn and soybeans are similar; they are established from seed, limited by water and nutrients, and are annual crops. In Indiana, corn and soybeans are both sown in the spring between April and May and harvested in the fall between October and November. The length of corn’s growth cycle depends on the properties of the plant
(e.g., commercially produced corn is selected based on the growing season). However, the average corn plant is ready for harvest in 125 days and soybeans are ready for harvest in about 120 days [USDA, 2010]. A fully developed corn plant consists of roots, a stalk, leaves, ears, and silk. A fully grown soybean plant consists of roots, a steam, leaves, and beans. Corn plants can be harvested in two main ways: the whole plant is cut at ground level and separated, or only the corn ears are harvested leaving the stalks, leaves, and roots behind. For soybeans, the majority of the plant is cut to ground level and the beans are harvested; the dried pod shell and other above-ground biomass residue is scattered back onto the soil surface.

![Figure 17. U.S. domestic corn use for years 1980-2013 adapted from USDA [2013b]](image)

In croplands, the soil contains the largest amount of carbon, with the biomass (i.e., corn or soybean plant) containing less than 5% of the total carbon [Lal, 2011]. Furthermore, 40-50% of the above-ground biomass can be removed during harvesting (nearly 100% of this biomass, if it’s used for silage). Because the residuals decompose relatively quickly, the type of harvest determines the amount of carbon released back to the atmosphere, as opposed to what is stored. When these crops are used for human and animal consumption, a majority of the carbon is returned to the atmosphere. The remaining biomass (i.e., stover) can also be utilized for animal consumption, for biofuels, or be incorporated in soil, leading to decomposition. The production of agricultural crops requires the use of equipment that emits CO₂, which can offset the quantity fixed. The agricultural production system type will determine the relative amounts of CO₂ that are emitted or sequestered. Figure 18 shows amounts of GHGs emitted from certain agricultural production processes in 2012, with the total agricultural emissions being 526.3 Tg CO₂-Eq in 2012.

**Data from Literature**

There is considerable literature on agricultural crop carbon sequestration, including how conservation tillage would increase SOC [Blanco-Canqui and Lal, 2007; Jarecki and Lal, 2003;
Kern and Johnson, 1993; Lal, 2004]. However, other reports discount the usefulness of storing carbon when conservation tillage is practiced [Ogle et al., 2012]. Baker et al. [2007] stated that conventionally tilled soils might support a deeper rooting pattern in crops leading to higher carbon input in deeper soils (i.e., deeper than 30 cm (12 in)). However, an Oak Ridge National Laboratory assessment of nine continuously cropped corn plots reported a national average increase of SOC in the top 30 cm (12 in) of soil of 595 kg C/ha/yr, with the average length of experiments being 25 years [West, 2001].

Figure 18. GHGs emitted from certain agricultural production processes in 2012 [U.S. EPA, 2014d]

3.2 Land Issues and Yields

Since the 1780s, residents of Indiana have realized the benefits of high-quality soils for cultivation. The potential of Indiana’s land for carbon sequestration is decided by many factors, including the amount of land being used for crop production, the land-management practices, and the properties of the soil. Thus, individual farms will have different sequestration potentials.

As Figure 19 shows, yields are higher for corn than for other major crops in Illinois. The increase in productivity from 1988 to 2008 can be largely attributed to genetic modification of hybrid corn species and improved management practices [Nafziger, 2009]. The climate and soil of Illinois, Indiana, and other Midwestern states are ideal for growing corn. To achieve annual corn yields of around 12,600 kg/ha (200 bu/ac) planting density needs to be between 62,000-99,000 plants/ha (25,000 and 40,000 plants/ac).

Figure 19. Corn, soybean and wheat yield trends in Illinois from 1990-2008 [Nafziger, 2009]
Figure 20 shows corn and soybean rotation effects with different levels of nitrogen fertilizer on grain yield in Nebraska. It is apparent that corn and soybean yields were increased with the addition of nitrogen fertilizer. However, this study was conducted over a two-year interval. Because climatic factors greatly affect total yield, studies with longer timeframes are needed for a more complete understanding of the relationship.

Land Usage
In Indiana, about 5,957,100 ha (14,720,396 ac) are used for agriculture, which is about 63% of the total area of the state, with 5,095,200 ha (12,590,633 ac) dedicated to croplands [USDA, 2014a]. In 2013, corn was grown on 2,263,800 ha (5,594,000 ac) in Indiana. Of this, 23% was managed using no-till, 15% using mulching, 22% using reduced-till, and 51% using conventional tilling [ISDA, 2014a]. The total soybean acreage was 2,202,500 ha (5,442,600 ac), with 52% being managed by no-till, 17% using mulch, 12% using reduced-till, and 13% using conventional-till practices [ISDA, 2014b].

Yields and Energy Content
Of the major agricultural crops, corn has one of the highest yields and energy content. Soybeans and corn can be grown on a variety of soil types and under a range of climatic conditions and still produce high yields. Over the last 100 years, improvement in farming practices has led to extremely high yields. Genetic improvement through breeding and genetic engineering has also contributed to this gain. Howell et al. [1998] used short-season bred hybrid corn to examine ways of reducing irrigation requirements and harvesting earlier. Genetic engineering has resulted in the development of insect-resistant and herbicide-tolerant plants, leading to improved yields and profits [Fresco, 2001]. Owen and Zelaya [2005] describe the benefits of using herbicide-resistant soybean and corn hybrids for weed control.

The amount of residue left on the soil surface depends on the cultivation and tillage system used. Heavy cultivation and tillage for corn will leave somewhere between 0% and 20% of the plant biomass on the soil surface. In contrast, light cultivation and tillage could result in 20% to 40% of residue, and no-till systems can leave 50% to 100% as residue. Soybean production with heavy cultivation and tillage could leave between 0% and 10% residue on the surface of the
field. If more residue is desired, tillage needs to be greatly reduced or stopped to achieve percentages between 20% and 40%; greater than 40% is needed to achieve a well-managed, continuous, no-till system. The amount of the residue relative to the percent ground cover is summarized in Table 12.

<table>
<thead>
<tr>
<th>Cover (%)</th>
<th>Soybeans residue-kg/ha (lbs/ac)</th>
<th>Corn residue-kg/ha (lbs/ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17 (15)</td>
<td>20 (18)</td>
</tr>
<tr>
<td>10</td>
<td>168 (150)</td>
<td>224 (200)</td>
</tr>
<tr>
<td>20</td>
<td>370 (330)</td>
<td>673 (600)</td>
</tr>
<tr>
<td>30</td>
<td>594 (530)</td>
<td>1,121 (1,000)</td>
</tr>
<tr>
<td>40</td>
<td>897 (800)</td>
<td>1,625 (1,450)</td>
</tr>
<tr>
<td>50</td>
<td>1,345 (1,200)</td>
<td>2,242 (2,000)</td>
</tr>
</tbody>
</table>

### Utilization of Crops and Residues for Carbon Storage

Agricultural crop carbon sequestration is difficult to quantify, as many factors affect the process. Environmental characteristics such as soil type, hydrological properties, topography, and climate are important. Furthermore, the developmental history of the crop and availability of nutrients influence the amount of carbon that is sequestered [U.S. DOE, 2008].

Most of the carbon fixed by agricultural crops is returned to the atmosphere. This complicates the potential for long-term storage of carbon that will result in reducing atmospheric CO₂ levels. Agricultural crop sequestration efficiency depends on SOC. The soil sink can store the carbon until saturation is reached. With conservation tillage management practices, it is estimated that the SOC can increase by 200-700 kg CO₂/ha/yr (178-625 lbs CO₂/ac/yr) [Lal, 2011].

### Conservation Agricultural Practices

According to the FAO [2006], conservation agricultural practices combine resource-saving crop production methods to conserve natural resources while attempting to achieve an acceptable profit from high and sustained yields. These practices include changes in cropping intensity; conservation tillage; cover crops; crop rotations; soil amendments; and any practice that adds biomass to the soil, causes minimal soil disturbance, and increases soil nutrient levels [Smith et al., 2008]. Also, the time of year and climate relate directly to loss of CO₂ from soil [USDA, 2007]. In particular, the amount of carbon lost relates directly to the volume of soil disturbed, timing and tillage practices used, with the lowest CO₂ losses resulting from conservative tillage (i.e. low and no-till practices) in the fall [Prio et al., 2004]. An increase in soil nitrogen from fertilization and manure applications, along with reduced tillage, helps to increase crop productivity and thus carbon sequestration [Christopher and Lal, 2007]. However, fertilizers can result in CO₂ emissions approximately equal to the amount sequestered in the soil, a factor that is not considered in many studies. Figure 21 depicts the optimum practices outlined in a report by Christopher and Lal [2007].

Integrating cover crops into corn-soybean reduced tillage and no-till operations for conservation practices is an import practice. For example, planting cereal rye after a shorter season corn or soybean variety can reduce soil erosion, sequester carbon, and reduce nutrient loss by increased cycling in the root zone, making it available for the next crop [PFI, 2014]. If corn stover is
removed for bioenergy, planting a cover crop can be beneficial to protect the soil from erosion and increase SOM [Pratt et al., 2013]. In addition, a cover crop could also be harvested as a bioenergy crop or a livestock forage crop [Smith and Kallenbach, 2006]. It should be noted, though, that planting cover crops requires additional resources (e.g., establishment, maintenance and harvesting costs, including equipment).

![Figure 21. Optimization of crop management practices to increase N availability and C sequestration potential adapted from Christopher and Lal [2007]](image)

No-till or reduced tillage are thought to be the most effective conservation agricultural practices to minimize SOM depletion, with reduced tillage thought to be the most effective [Lal, 2011]. By definition, conservation tillage is any cropland system in which one-third or more of the crop is left as residue on the soil surface [CTIC, 2014]. This results in higher percentages of the soil surface covered, allowing for an increase in inputs to the SOC pool [Horowitz et al., 2010]. A review of 32 long-term experiments revealed that conversion from conventional to no-till farming practices sequestered an additional 168 kg C/ha/yr (150 lbs C/ac/yr) in the top 30 cm for various crop types [West, 2001]. As stated previously, more than half (52%) of Indiana’s soybean operations are now using no-till practices. However, 51% of the corn acreage is still under conventional tillage; no-till and reduced tillage is practiced on 23% and 22%, respectively. Figure 22 shows the adoption rates of no-till (percent of land) for soybean in Indiana by county and Figure 23 shows the same for corn. Clearly, no-till farming is most popular in the south-central part of the state. This can be partially attributed to the differences in topography of the state. Central and northern Indiana are much flatter than southern Indiana, and steeper slopes have shallower soils.

### 3.3 Economic and Policy Implications

An advantage of using agricultural crops for carbon sequestration is the presence of an established infrastructure. McCarl and Schneider [2000] estimated the cost for agricultural carbon sequestration between $10-25 per ton, while forestry and industrial sectors were $13-26 and $200-250 per ton, respectively. The change from conventional management practices to conservation practices can save money and resources. These practices do not require extra labor, but additional pesticides and fertilizers are needed, and GHG emissions result from their production and application. Additionally, when switching to conservative management practices, economic opportunities are lost. These opportunities include the use of corn stover as animal feed, livestock bedding, and a feedstock for biofuel production, not to mention the potential for reduced yields.
Figure 22. 2013 no-till soybean percentages by county for Indiana [USDA, 2013]
2013 No-till Corn Percentages

Figure 23. 2013 no-till corn percentages by county for Indiana [ISDA, 2014]
End-Uses of Corn and Soybeans: Food vs. Fuel

Traditionally, corn and soybeans have been produced for humans and feed for animals. With the recent push to create a reliable and sustainable source of renewable energy, corn and soybean crops have been used as feedstocks for producing biofuels. Corn is principally used as a feedstock to create ethanol, while soybeans are mainly used as a feedstock for biodiesel. This competing demand for traditional food crops has an effect on food supplies. The dilemma is not easily resolved, as many global issues affect corn and soybean yields and end-uses. Analysis of a large number of studies led to the conclusion that when crops are used for biofuels, there is a direct impact on the food and feed supply, which in turn causes an increase in their prices [HLPE, 2013]. The higher prices provide incentives for farmers to increase their acreage under production and boost yields. Land-use change is a major contributor to GHG emissions, particularly if grasslands and forest are converted to annual-crop production. Figure 24 demonstrates how biofuels produced from feedstocks derived from energy plantations affect carbon sequestration.

Figure 24. Energy plantation’s biofuels effects on C sequestration adapted from Lal [2008]

With the increasing use of corn for ethanol production, U.S. farmers have been growing corn exclusively on many acres that historically had been alternately cropped with soybean, and cultivating marginal lands or pastures. While this potentially increases the amount of carbon sequestered in agricultural soils, soybean production is decreasing [USDA, 2014d]. In addition, maintaining productivity in continuous corn rotations requires more tillage and fertilizer inputs than alternately with soybean [Kim and Dale, 2005]. Typically, energy production is favored over food production purely on economic grounds.

Implications of Utilizing Residues as a Feedstock for Biofuel Production

Corn and soybean residues also offer the potential as a cellulosic feedstock for biofuel production. A study completed by Blanco–Canqui et al. [2006] on the utilization of corn stover as a primary bioenergy feedstock evaluated the removal of stover on no-till and conventionally tilled continuous corn management. The study tested five rates of corn stover removal (0, 25, 50, 75, and 100%) and data were collected for 2.5 years. The study revealed that stover removal higher than 25% led to a decrease in SOC and crop yields [Blanco-Canqui, 2006]. The stover removal also caused a decrease in the soil nutrients, which led to an increased need for fertilization. A study by Brechbill et al. [2011] looked at the economics of utilizing corn stover for biofuel production. The removal rate greatly influenced the cost and yield of stover and was directly correlated with the amount of soil erosion, compaction, and nutrient loss.

Summary of CO$_2$ Benefits from Responding to EPA Policy Changes

Agricultural soils have a high soil carbon sequestration potential, as they cover about 4,960 Mha (12,260 Mha) globally and may annually sequester 0.4 to 0.8 Pg C in soils [Lal, 2004]. In
general, the SOC concentration of agricultural cropland is lower than that of non-cultivated soils. Lands that were previously covered with forests, prairies, and other natural ecosystems had higher SOC levels. If agricultural practices are modified to increase sequestration, then the crops are only returning to the soil carbon that was released by cultivation in the past. This does not mean that agricultural crops do not offer an immediate carbon sequestration strategy to reduce atmospheric CO₂ concentrations; on the contrary, agricultural crop sequestration can be implemented as a near-term strategy, offering time for the development of new carbon-sequestration strategies [Graming, 2010].

4.0 Dedicated Energy Crops for Carbon Utilization

For this report, only short-rotation woody crops and temperate-zone perennial grasses will be considered as dedicated energy crops. Specifically, hybrid poplar, Miscanthus, and switchgrass will be investigated, because they offer great CO₂ emissions reduction and storage potential. There are many advantages to using energy crops in states reliant on coal-fired power plants. The crops are relatively inexpensive to establish and require little maintenance. According to Heaton et al. [2004], qualities that ideal fuel crops should possess are: good energy balance; efficient utilization of light, water and nutrients; C₄ photosynthesis; available cultivation and pest-control measures; minimal need to change land use or farm machinery; and environmental benefits. Energy balance or energy return on investment refers to the required energy inputs (e.g., fossil fuels) versus outputs to society [Hall et al., 2009]. Maximum efficiency of light use involves having complete canopy cover to maximize light interception, minimize light available to competing vegetation, and simultaneously minimizing herbicide requirements. Sufficient water is needed for the plants to achieve their maximum growth potential and remain green throughout the growing season. Harvested biomass should also have minimal moisture content at the time of harvest, because the added cost associated with the water in the biomass, including transportation fossil-fuel carbon emissions and the need for post-harvest drying, which requires additional energy inputs. Water-use efficiency is important, because significant inputs of energy are required for irrigation, not to mention infrastructural costs and the additional demand it places on water resources.

Nutrient-use efficiency involves efficient recycling and maximal capture of nutrients from the soil. C₄ is the most efficient form of photosynthesis, possessing the highest potential for converting sunlight energy into stored energy. C₄ plants also tend to have higher efficiencies of nitrogen and water use. With regard to cultivation, it is important to select a crop that has minimal plowing, planting, and chemical requirements. Pest control involves selecting species that are least susceptible to diseases and insects. Farm equipment is expensive, so it is vital to avoid the purchase of new, specialized equipment and minimize the need to retrofit existing machinery for establishing, maintaining, and harvesting the crops. Finally, ideal fuel crops should have some kind of environmental benefit (e.g., provide refuge for wildlife, minimal chemical inputs, and/or have the ability to sequester carbon in the soil).

4.1 Overview of Carbon Cycle for Dedicated Energy Crops

The carbon cycle for dedicated energy crops varies by crop. Woody energy crops can be established using seed or vegetative propagules (clones of a plant are produced using a stem or
branch segment), depending on the species, but have a growth cycle similar to the other deciduous hardwoods discussed above. Poplars can be coppiced, a method by which the tree is cut close to the base and new shoots emerge from dormant, preformed buds in the remaining stump. Of course, the yield from poplar is affected by the length of the coppice cycle. In addition, recent research has shown that poplars harbor an endophyte that appears to be capable of fixing atmospheric nitrogen. Endophytes are microorganisms that live within the cells of their host plants without harming it, and even promote plant growth and health [Taghavi et al., 2008]. Because of the nitrogen-fixing endophyte, the need for nitrogen fertilization may be greatly reduced with poplars. Table 13 includes characteristics of short-rotation woody crops and herbaceous crops.

Crop Types

The dedicated energy crops such as hybrid poplar and perennial grasses have advantages over native hardwoods and agriculture crops and can be utilized in the Midwest. Switchgrass and Miscanthus tolerate cold winter temperatures, can be grown in a broad range of soil types, and traditional growing techniques can be used for them [Khanna et al., 2008]. These plant species can be planted densely, at a low cost, and require little maintenance. French et al. [2006] and Gallagher et al. [2008] have described uses of poplars in different areas of Indiana.

According to Parrish [2012], established uses for switchgrass include: erosion control in waterways, vegetative filter strips, reclamation or stabilization of sand dunes, and wildlife habitat. Furthermore, they can be used as energy feedstocks for direct combustion or conversion to liquid or gaseous fuels and as a source of pulp for paper. Shonnard et al. [2006] described switchgrass as a perennial grass that can be used for a variety of purposes, have minimal nutrient requirements, and do not require irrigation. Furthermore, switchgrass can be established from seed, which is available commercially [Downing et al., 2011] and can be planted using conventional agricultural equipment.

Heaton et al. [2004] reported that herbaceous perennials, such as Miscanthus, require fewer inputs than corn and soybean. For example, they only need to be re-planted every 10 to 20 years; minimal nitrogen fertilization is required; and when used for combustion, much less processing is needed than for other energy crops. In addition, Miscanthus is exceptionally cold tolerant compared to traditional crops. Herbaceous perennials can have higher yields than many forest crops and can be managed using existing farm equipment. Miscanthus can also be combusted directly with coal, as is being done in Europe [Heaton et al., 2004]. Table 14 lists advantages Miscanthus has over corn and short-rotation coppice. The table is organized by 14 categories and indicates (with a plus sign) the characteristics each crop possesses. Clearly, Miscanthus has the most positive traits for the categories listed; however, there are disadvantages not listed in the table. Short-rotation coppice (poplar and willow for this study) have many of the same attributes, while corn does not. Of course, corn is widely grown as a food and feed crop, whereas short-rotation woody crops and Miscanthus are not. However, corn grain has recently been widely used as a feedstock for bioethanol production.

Rates of biomass accumulation by hybrid poplar have been studied from the southeast to northeasterm states, such as Minnesota [Garten, 2002]. According to Hansen [1993], poplars have been shown to sequester more carbon than traditional row crops on previously tilled soils. With their exceptional growth, poplars have been shown to be effective for carbon sequestration and energy production [Fang et al., 2006]. In fact, poplar has been described as a model woody biomass
feedstock because of its many favorable attributes, including an available genome sequence, ease of transformation, and rapid growth [Yuan et al., 2008].

Shonnard et al. [2006] described commercial interest in utilizing biomass resources to produce energy-related products. They investigated the biomass resources, harvest, conversion technologies (for the production of liquid fuels), other existing technologies, supply systems, and business scenarios. Sartori et al. [2006] provided an overview of constraints, carbon fluxes, estimation methods, SOC sequestration rates, productivity, and land availability associated with liquid-fuel production.

Table 13. Factors affecting SOC associated with different energy crops [Sartori et al., 2006]

<table>
<thead>
<tr>
<th>Crop Characteristic</th>
<th>Woody short-rotation</th>
<th>Herbaceous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial SOC loss due to site preparation followed by recovery</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Rapid SOC recovery in presence of low actual	extsuperscript{1} and high attainable	extsuperscript{2} yield levels</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Rapid SOC recovery with perennial grasses on CRP land or in presence of low actual	extsuperscript{1} and high attainable	extsuperscript{2} levels</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SOC protection of the heavy fraction of SOM. Low SOC protection in the absence of clay mineralogy</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Deciduous hardwood species increase SOC</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Effect of deep-rooted species (&gt;1 m)</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>N-fixing species enhance SOC sequestration</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>No SOC detectable change with land use conversion if span &lt;10 yr or in presence of similar SOC actual	extsuperscript{1} and attainable	extsuperscript{2} levels</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>No SOC detectable change with land use if span &lt;10 yr or in presence of similar SOC actual	extsuperscript{1} and attainable	extsuperscript{2} levels</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Soil fauna dominated by earthworms increases SOC</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Yields observed in a particular field setting

\textsuperscript{2}Yields predicted or observed increase

Growth Cycle, Carbon Uptake, and Carbon Sequestration

The growth cycle is different for woody and herbaceous dedicated energy crops. Poplars are known for their rapid growth and ease of establishment. Their production cycle includes: site preparation, plant establishment, growth management, and harvest [Shonnard et al., 2006]. They grow faster than the hardwoods described in section 2.0 above, can be planted at high densities, and are deciduous. Unlike agricultural crops, poplars can be harvested in the winter. This helps reduce soil erosion and compaction and allows for harvesting at any time biomass is needed. In addition, poplars accumulate more carbon over time in the whole-plant biomass than herbaceous plants, since they do not die after the growing season.

Switchgrass and Miscanthus have similar growth cycles. Switchgrass allocates much of its energy to developing an extensive root system and will only attain 33-66% of its maximum above-ground yield during its first two years, with faster growth thereafter [McLaughlin and Adams-Kszos, 2005]. It is a warm-season grass whose native range is east of the Rocky Mountains, extending into Mexico and Canada [Walsh et al., 2003]. Switchgrass can be planted
on lowlands and uplands and can be managed and harvested in the same way as traditional hay crops.

Table 14. Comparison of Miscanthus, corn, and short-rotation coppice [Heaton et al., 2004]

<table>
<thead>
<tr>
<th>Crop Characteristic</th>
<th>Corn</th>
<th>Short-rotation coppice</th>
<th>Miscanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₄ photosynthesis</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Long canopy duration</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Perennial-no need for annual tillage or planting</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>No known pests or diseases</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid growth in spring to out compete weeds</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Sterile: prevent ‘escape’</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stores C in soil (soil restoration and C sequestration tool)</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Partitions nutrients back to roots in fall--low fertilizer-needs</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Low nutrient content (&lt; 0.2 g/MJ N and S)--clean burning</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>High water-use efficiency</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Dry down in field--zero drying costs</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good winter standing-harvest when needed/no storage costs</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Utilizes existing farm equipment</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Alternative markets--quality paper, building materials, etc.</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

4.2 Land Issues and Yields

Dedicated energy crops can be grown in much of the continental U.S. and Hawaii, but poplars, switchgrass, and Miscanthus can be grown across a wide geographic range [U.S. DOE, 2006; Figure 25], including the entire Midwest and many surrounding states. They also can be grown in regions not shown on the map, but data regarding varieties, yields, and production practices were not available at the time the U.S. DOE report was prepared.

Figure 25. Herbaceous and wood crop possibilities by the U.S. DOE [2006]
Land Availability

The advantage of poplars, switchgrass, and *Miscanthus* as dedicated energy crops is that they can be grown in a variety of soil types, elevations, etc., making them the most flexible of biomass crops. They can be grown on farms used for traditional row crops, in woodlots where hardwoods are typically grown, and on disturbed sites that are unsuitable for either of these uses. Obviously, it is economically impractical to replace food crops with dedicated energy crops. Therefore, the displacement of food and feed crops, such as corn, on prime agricultural land is not being advocated, because it could lead to food shortages and price increases [Kunycky and Sharader-Frechette, 2013], and farmer’s would not displace the higher value corn. To use energy crops to achieve the desired carbon offsets, land availability must to be addressed.

Rehabilitation of Marginal Lands

Poplar, switchgrass, and *Miscanthus* can be grown on less desirable sites than agricultural crops, as well as being able to be planted more densely than native hardwoods. For example switchgrass is an ideal crop to grow on marginal lands in southern Iowa. This grass is native to the state and it grows well with moderate inputs. Because it is perennial, it can protect soil against erosion, improve water quality, and provide wildlife habitat. In addition, it can help sequester carbon and can be used for electricity generation [Duffy and Nahou, 2001].

Poplars are ideal for brownfield sites in urban settings. These plants can remove contaminants from soil on old industrial sites, as has been demonstrated throughout the Midwest and elsewhere. In Indianapolis, IN, a project funded through an urban forestry grant used poplars to remediate brownfield sites and was used for urban farming [Harrell, 2009]. In Elkhart, IN, the Delta Institute [2011] investigated the use of poplars grown on brownfield sites to provide a local wood source. Westphal and Isebrands [2001] investigated the use of poplars to clean up a contaminated landfill in Chicago. In England, Dickinson et al. [2006] and French et al. [2006] used poplars as an efficient and cost-effective method for remediating low-level brownfield sites. Not only is the contaminated soil rehabilitated, these projects add jobs to local economy and help people connect with the community in which they live.

Yields and Energy Content

Although there is a lot of variance in reported data, most estimates have shown a reduction of 90% in CO₂ emissions from the use of poplars and grasses [Union of Concerned Scientists, 2007]. One key feature of both poplars and these grasses is that they have higher energy content than corn and soybeans. Sartori et al. [2006] reported that switching from corn to switchgrass as a feedstock for ethanol production could possibly result in net energy gains as high as 15 fold and reductions in CO₂ emissions as high as 20 fold. However, it is much more difficult to process ethanol from switchgrass than from corn. Switchgrass (17.0-18.1 MJ/kg), *Miscanthus* (17.1-19.2 MJ/kg), and poplar (18.5-19.0 MJ/kg) have comparable heating values (i.e., heat produced from complete combustion) to those of corn grain (18.8 MJ/kg) and corn stover (16.2-17.7 MJ/kg) [Jenkins et al., 1998; Lewandowski et al., 2003; Mani et al., 2004; McKendry, 2002; Patzek, 2004]. Because the biomass yields of energy crops are greater than what can be derived from corn stover, more energy can be derived from them. Also, because poplars do not have to be harvested at a certain time, in contrast to corn, which is harvested only in the fall, poplar biomass can be “stored on the stump” until it is needed or the economic conditions are right. In this way, the energy is stored at no additional cost.
Yields for switchgrass are estimated to be 6.73 ton/ha (3 T/ac) the first year of harvest and 11.2 ton/ha (5 T/ac) thereafter [Brechbill and Tyner, 2008]. In the Corn Belt, which includes Indiana, the yields were estimated to be 12.15 ton/ha (5.42 T/ac) and the production cycle of a plantation is 10 years. Annual switchgrass yields for field trials conducted in three Midwestern states are shown in Table 15. Average yields range from 9.47 ton/ha (3.83 T/ac) in Kansas to 20.6 ton/ha (8.34 T/ac) in Nebraska. In addition, Liebig et al. [2008] conducted a five-year study of switchgrass on four farms in Nebraska where an average of 2.92 ton C/ha (1.30 T C/ac) were stored at a depth of 1.22 m (4 ft).

Table 15. Midwest site’s average switchgrass yields [McLaughlin and Adams-Kszos, 2005]

<table>
<thead>
<tr>
<th>State</th>
<th>Time planted and time evaluated</th>
<th>Average yield over sites-ton/ha (T/ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nebraska</td>
<td>1998 and 1999-2001</td>
<td>16.3- 20.6 (7.3-9.2)</td>
</tr>
</tbody>
</table>

Heaton et al. [2004] showed that Miscanthus can yield approximately 33 ton/ha (13.3 T/ac) in Illinois; however, this depends greatly on the local soil conditions. Yield data for Miscanthus planted on sites in Kentucky, Nebraska, and New Jersey are summarized in Table 16. The study also evaluated the effect nitrogen fertilizer. These data were collected the second year after planting but maximal yields were not achieved until years 3 to 5. Further analysis is needed to determine if there were any soil or climate variations that confounded the results. According to Khanna et al. [2008], field trials have shown that in the Midwest Miscanthus can have twice the yields as switchgrass; this differential is even greater in Europe, where much research has been done with Miscanthus.

Commercial poplar plantations have produced 24.7 ton/ha/yr (10 T/ac) in Minnesota and 20 ton/ha/yr (49.4 T/ac) in the Pacific Northwest [Volk et al., 2010]. Zalesny et al. [2009] reported yields of between 4 and 25 ton/ha/yr at various locations in Iowa, Minnesota, and Wisconsin in plantations that were established beginning in 2000. Yields varied greatly depending on the age and location of the stand and the genotype that was planted. For example, Cannell [2003] calculated, using a simplified scheme of cultivation and transportation, that the ratio of energy primary output to input was between 12 and 37.

Table 16. Midwest and Northeast average Miscanthus yields [Downing et al., 2011]

<table>
<thead>
<tr>
<th>Nitrogen Fertilizer kg/ha (lbs/ac)</th>
<th>Location and yields-ton/ha (T/ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lexington, KY</td>
</tr>
<tr>
<td>0</td>
<td>16.8 (7.5)</td>
</tr>
<tr>
<td>61 (54)</td>
<td>17.5(7.8)</td>
</tr>
<tr>
<td>120 (107)</td>
<td>16.8 (7.5)</td>
</tr>
</tbody>
</table>

Challenges: Harvesting, Storage, and Transportation

Dedicated energy crops do not come without challenges. In particular, there may be the need for specialized equipment for planting and harvesting can be difficult for the crops in relatively small areas, where commercial farming equipment cannot be used. The storage of the switchgrass and Miscanthus biomasses for co-firing applications is also problematic and may be
a barrier to adoption and profitability. The grasses are only harvested in the fall, but power plants run year-round. In a report on a proposed biomass boiler in Jasper, IN [Shaddix, 2011], it was noted that the combustion of herbaceous crops can increase the amount of slag formation and fouling (unwanted material buildup on surfaces) when combusted and may lead to boiler downtime for maintenance and cleaning.

For grasses, a key issue is where and how to store the biomass, and whether enough of it be stored to meet the need throughout the year. Additionally, Epplin et al. [2007] stated that, compared to corn grain, switchgrass is bulky (low mass/volume ratio) and difficult to transport. For poplars, storage is not problematic because they can be harvested at any time of the year. In contrast, grasses more challenging to transport and store because low density and commercially available machinery to bale wood are limited and very expensive (unlike agriculture large square balers).

Although the herbaceous energy crops cannot be used as food, the land on which they are grown could be used to produce perennial forage crops for livestock. In particular, if the market price is high or policies promote their production, growing energy crops could result in the displacement of livestock forage and food crops, which would impact food supply.

Biomass collection is another concern. Table 17 indicates the average annual labor requirements for various crops. The values are based on machine operation times (hours per hectare), with poplar estimates including hand planting, and were calculated using American Society of Agricultural and Biological Engineers standards. These estimates only reflect labor hours and marketing time. Annual labor averages for Miscanthus and switchgrass are similar. Labor requirements for poplar are the highest, with “old-field” crops having the lowest. “Old field” refers to natural successional re-growth on fallow land with no agronomic inputs; thus, harvest and handling are the only production-related costs. If these types of biomass are transformed into ethanol or other liquid fuel(s), then there will be significant reductions in GHG emissions relative to grain-based feedstocks and their associated processes [Bickham and Thomas, 2010]. Energy use and the emissions associated with harvesting, storage, and transportation are major concerns and can greatly reduce the benefits of bioenergy.

Table 17. Annual field labor times requirements by crop system [James et al., 2010]

<table>
<thead>
<tr>
<th>Crop</th>
<th>Annual average-hr/ha (hr/ac)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous corn + stover</td>
<td>3.95 (1.60)</td>
</tr>
<tr>
<td>Corn-soybean-canola</td>
<td>2.99 (1.21)</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>1.46 (0.59)</td>
</tr>
<tr>
<td>Grass mix + clover</td>
<td>1.70 (0.69)</td>
</tr>
<tr>
<td>Poplar</td>
<td>5.28 (2.14)</td>
</tr>
<tr>
<td>Native prairie</td>
<td>1.48 (0.60)</td>
</tr>
<tr>
<td>Old field</td>
<td>1.02 (0.41)</td>
</tr>
</tbody>
</table>

4.3 Economic and Policy Implications

Dedicated energy crops have the potential to impact the economy, the environment and power-plant operators in a positive way. Poplars can be grown to supply wood for certain industries (e.g., the recreational-vehicle industry in Indiana). Wood would not have to be imported if there is a local source, thus saving transportation costs and keeping money local, while adding jobs.
Furthermore, the USDA’s Conservation Reserve Program (CRP) is a cost-share and rental payment program that, with modifications (e.g., allowing coppicing), can be used to plant dedicated energy crops and achieve its goals.

Khanna et al. [2008] evaluated the costs of producing Miscanthus and switchgrass for bioenergy in Illinois, compared to corn and soybean (Table 18). For the study, the break-even delivered cost is the minimum price per delivered (40 km (24.9 mi) away) ton of dry matter that a landowner would need to receive to be willing to switch to growing Miscanthus or switchgrass. They concluded that switchgrass has a higher break-even delivered cost because the yields per hectare are greater for Miscanthus (49.30 ton/ha (21.99 T/ac)) than switchgrass (14.28 ton/ha (6.37 T/ac)).

Table 18. Annualized production costs of perennials and row crops [Khanna et al., 2008]

<table>
<thead>
<tr>
<th>Cost items ($/ha)</th>
<th>Switchgrass</th>
<th>Miscanthus</th>
<th>Corn</th>
<th>Soybean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer</td>
<td>57.4</td>
<td>40.4</td>
<td>132.5</td>
<td>59.5</td>
</tr>
<tr>
<td>Chemicals</td>
<td>4.2</td>
<td>1.3</td>
<td>76.6</td>
<td>89.0</td>
</tr>
<tr>
<td>Seed</td>
<td>15.7</td>
<td>23.7</td>
<td>88.7</td>
<td>47.4</td>
</tr>
<tr>
<td>Interest on operating inputs</td>
<td>5.4</td>
<td>4.6</td>
<td>13.9</td>
<td>9.1</td>
</tr>
<tr>
<td>Storage/drying/crop insurance</td>
<td>23.9</td>
<td>87.7</td>
<td>59.3</td>
<td>27.2</td>
</tr>
<tr>
<td>Machinery</td>
<td>222.4</td>
<td>673.6</td>
<td>202.6</td>
<td>173.0</td>
</tr>
<tr>
<td>Transportation</td>
<td>45.7</td>
<td>157.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Annualized operating costs</td>
<td>374.7</td>
<td>988.9</td>
<td>573.9</td>
<td>405.2</td>
</tr>
<tr>
<td>Annualized yield (ton/ha)</td>
<td>5.8</td>
<td>20.0</td>
<td>9.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Opportunity cost of land</td>
<td>192.8</td>
<td>192.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Break-even delivered cost including opportunity cost of land ($/ton)</td>
<td>98.2</td>
<td>59.2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The annualized costs per unit mass for the dedicated energy crops are summarized in Table 19. This is a simplified example of the costs included in the Billion-Ton Study [Downing et al., 2011]. The cost depends on the site quality and inputs and prices vary by crop. For example, the five-year average costs for a switchgrass farm (including labor and land) in Nebraska were $60/ton; however, experienced producers can have costs between $38 and $43/ton [Perrin et al., 2008]. Khanna et al. [2008] estimated the costs for Miscanthus production per ton to be between $37 and $52 for farm-gate break-even prices. Furthermore, Jain et al. [2010] reported break-even costs to produce Miscanthus of $46/ton in Missouri and $139/ton in Minnesota. Finally, in research plots (for a 12-year rotation system), the University of Minnesota estimated that the costs associated with poplar range from $25 to $60 per dry ton [Jain et al., 2010]. It should be noted that prices per acre are difficult to obtain, because commercial-plot production and prices are proprietary.

Implications for Power Plants, Co-firing Applications, and Biofuels

The use of dedicated energy crops could have an impact for co-firing applications [Demirbas, 2005]. This includes using them to supplement coal for power plants, where the energy crops can be burned with minimal infrastructural change. The impact of the energy crops for use in liquid biofuels is also of interest, given that dedicated energy crops have a greater energy capacity than the traditionally used corn. For example, Downing et al. [2011] described a five-year study
conducted in Nebraska that estimated switchgrass ethanol production of 3,479 L/ha (372 gal/ac) on marginal soils. This was equal or greater to that of both the grain and stover of no-till corn on a rain-fed site with marginal soil.

Table 19. Annualized costs for dedicated energy crops

<table>
<thead>
<tr>
<th></th>
<th>Switchgrass</th>
<th>Poplar</th>
<th>Miscanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yields ton/ha (T/ac)</td>
<td>11.2-17.3</td>
<td>17.3-24.7</td>
<td>14.6-29.7</td>
</tr>
<tr>
<td></td>
<td>(5.0-7.7)</td>
<td>(5.0-7.7)</td>
<td>(6.5-13.2)</td>
</tr>
<tr>
<td>CO₂ absorbed at 50% biomass C content ton/ha (T/ac)</td>
<td>20.5-31.7</td>
<td>31.7-45.3</td>
<td>14.6-29.7</td>
</tr>
<tr>
<td></td>
<td>(9.1-14.1)</td>
<td>(14.1-20.2)</td>
<td>(6.5-13.2)</td>
</tr>
<tr>
<td>Costs $/ton ($/T)</td>
<td>38-60</td>
<td>25-60</td>
<td>37-59</td>
</tr>
<tr>
<td></td>
<td>(34-55)</td>
<td>(23-55)</td>
<td>(33-54)</td>
</tr>
<tr>
<td>Costs per ton CO₂ $/ton•CO₂ ($/T•CO₂)</td>
<td>20.7-32.8</td>
<td>13.6-32.8</td>
<td>20.2-32.2</td>
</tr>
<tr>
<td></td>
<td>(18.5-30.0)</td>
<td>(12.5-30.0)</td>
<td>(18.0-29.5)</td>
</tr>
</tbody>
</table>

Figure 26 gives a simplified example of co-firing with of a mixture of 85% coal and 15% biomass. GHG emissions were reduced from 1.04 kg CO₂-Eq/kWh (2.30 lbs CO₂-Eq/kWh) from a coal power system to 0.868 kg CO₂ equivalent/kWh (1.91 lbs CO₂-Eq/kWh). According to Clifton-Brown et al. [2004], 1 dry ton of Miscanthus biomass used as a replacement for coal in electricity generation displaces 0.5 tons of carbon being emitted from coal. This is an important advantage over agricultural crops, such as the stover from corn and soybeans. When accounting for cultivation and transportation of energy crops, Cannell [2003] gave values of 10-40 kg C emissions for every 500 kg C produced. However, perennial grasses are harvested once per year (in the fall) and economical storage systems have not been developed.

Figure 26. Energy balance for co-firing biomass with coal [Spath and Mann, 1999]
Tillman [2000] investigated the use of wood waste and biomass from hybrid poplar and switchgrass for co-firing in a pulverized coal boiler. From modeling of different electric companies (including the NIPSCO plant in Michigan City, IN), the general consensus was that there would be minimal physical connections between the biomass and coal feeders. The reason for connections is that plant biomass is separated prior to co-firing. Furthermore, blends can be stocked up and stored, combusted with minimum impact on boiler operations, and there are minimal stops in normal operations. For co-firing with biomass, there are reductions in the efficiency of the boilers; however, they were deemed to be manageable. Furthermore, there are reductions in NO\textsubscript{x} emissions and CO\textsubscript{2} emissions are reduced by 2.7 to 3.15 tons (5,952 to 6,945 lbs CO\textsubscript{2}) per ton of biomass combusted. If combined with a value of 18.5 GJ/ton of biomass [as reported by Cannell, 2003], the emissions per unit of energy produced would be between 146 kg CO\textsubscript{2}/GJ to 170 kg CO\textsubscript{2}/GJ.

Estimated feedstock requirements to meet U.S. liquid transportation fuel needs are summarized in Table 20. These estimates assume there are no indirect land-use change and no competition with the food supply. For the corn stover, adequate amounts remained on the field to protect and sustain the soil. For the 2020 estimate, biomass feedstock production was assumed to take place on 59 Mha (24 Mac) of CRP land and that wheat and hay straws followed historical trends. It is clear from these data that dedicated energy crops have great potential for supplying biofuel needs. However, given the low cost of fossil fuels, for the implementation of biofuels there will need to be incentives to complement or replace fossil fuels [Schulze et al., 2012].

<table>
<thead>
<tr>
<th>Feedstock Type</th>
<th>2008 (million ton)</th>
<th>2020 estimate (million ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>76</td>
<td>112</td>
</tr>
<tr>
<td>Wheat and grass straw</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Hay</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Dedicated fuel crops</td>
<td>104</td>
<td>164</td>
</tr>
<tr>
<td>Woody residues</td>
<td>110</td>
<td>124</td>
</tr>
<tr>
<td>Animal manure</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>90</td>
<td>100</td>
</tr>
</tbody>
</table>

Conservation Reserve Program (CRP)

The CRP is the largest agricultural conservation program in the U.S. This program helps reduce soil erosion, enhance water supplies and quality, and increase wildlife habitat [Sullivan et al., 2004]. Also, it is intended to reduce damage caused by floods and other natural disasters. Through this program farmers are encouraged to transform some of their farmland into grasslands, especially the lower quality lands. They are paid to take highly erodible land out of production to not only prevent soil erosion but also improve air quality (dust) and avoid water contamination. Farmers are expected to retire the environmentally sensitive land for a period of 10-15 years. However, with rising levels of crop prices, farmers may elect to not renew their contracts, or attempt to cancel them. Therefore, there is no guarantee that the land will not be used for crops, reducing the benefits this program is intended to provide.

The concern with the CRP program, with respect to dedicated energy crops, is that farmers are not required to plant certain species. Rules governing the program could be modified to include a
dedicated energy crop requirement. If farmers were obligated to plant switchgrass or *Miscanthus*, it would help the government realize its renewable-fuel goals; although if the landscape is dominated by one or two species, pest and ecosystem level problems could arise, with the lack of biodiversity. There would likely be a decrease of biodiversity with poplars [Schulze, 2012], but not to the same extent. Currently, 14 Mha (35 Mac) are enrolled in the CRP, which sequester 48 Mt CO$_2$ (1.06 x 10$^{11}$ lbs CO$_2$) annually [Bickham and Thomas, 2010]. However, in 2010 contracts for about 10.5 (26 Mac) were set to expire. If the prices for corn and soybean are high, farmers are likely put the land back into crop production.

According to Lee et al. [2007], switchgrass grown on CRP land could be used as a bioenergy feedstock rather than converting the land to traditional crops after the contract expires. Land enrolled in the CRP and planted with perennial grasses sequesters more carbon than traditional crops. For example, it has been shown that up to 1.1 ton C/ha was sequestered on CRP land during the first five years of the program. Moreover, switchgrass grown for biomass has the potential to significantly increase SOC. If converted to traditional row crops, many of the benefits of the CRP program would be lost.

Because the goal of the CRP is to take land out of production, trees planted on land that is set aside cannot be harvested. However, if poplars are harvested through coppicing rather than replanting, their root systems remain in place; thus, the objectives of the program can still be met. According to Ruark et al. [2006], if hybrid poplar were grown on 15.4 Mha (38 Mac) (2006 area), it would annually yield approximately 190 million DT of wood/yr (4.19 x 10$^{11}$ lbs /yr) for use as a biofuel. At 16 million BTU/ton/yr, that is equivalent to approximately 3 QUAD/yr. This assumes a sustained yield of 12.36 ton/ha/yr (5.51 T/ac/yr), which has been documented in the north-central of the U.S. Yields of 17.30 ton/ha/yr (7.72T/ac/yr) are possible on more productive sites.

**Summary of CO$_2$ Benefits Relative to EPA Rule**

Using dedicated woody species and herbaceous perennial grasses for carbon sequestration has many potential benefits. They can be used to sequester carbon, ameliorating its effect on climate change. The carbon fixed by dedicated energy crops would be part of a closed cycle and reduce the need for coal at power plants. In practice, efficiency losses in energy generation would need to be accounted for, in case energy crops were not planted about carbon sequestration and carbon emissions associated with producing feedstock. Dedicated energy crops can replace row crops on fragile and marginal lands where the end-use is biofuel without negatively impacting the food supply. Poplar biomass is useful for various manufacturing industries in Indiana, in addition to biofuel applications, with the added advantage of just-in-time harvesting. Finally, a combination of dedicated energy crops provides one option for meeting the mandates being imposed by EPA’s CO$_2$ policy change.

**5.0 Summary**

The EPA’s new regulations for CO$_2$ emissions from coal-fired power plants are leading to an examination of different methods that can be used to meet these targets. The BSER has laid out a nationwide approach for improving the efficiency of power plants, utilizing low-emission power sources and increasing energy-user efficiency.
Carbon, a key component of living matter is cycled through respiration by animals, plants and microorganisms, or by direct combustion. CO₂ is considered a GHG because it absorbs electromagnetic radiation from the sun or earth and reflects some of it back to the surface, essentially insulating the earth against heat loss. A rapid increase in atmospheric CO₂ levels has been caused by the combustion of fossil fuels, deforestation, and agricultural practices. This has perturbed the balance of the natural carbon cycle. Deforestation and agriculture practices also result in the liberation of the carbon stored in biomass and soil.

Terrestrial sequestration is considered a major carbon-storage strategy because of its relatively low costs, ease of installment, and positive effect on the health of the environment. This report examined three types of terrestrial carbon storage: agricultural crops, hardwoods, and perennial grasses. These plants utilize photosynthesis to sequester carbon in biomass, some of which contributes to SOC. The soil sink offers the largest opportunity for carbon storage; however, the necessary timeframe for carbon storage is longer than the 30-year EPA regulation.

Recommended best practices for agricultural land management include no-till and low-till farming, as well as cover cropping. Hardwood trees may require management (e.g., thinning) to maintain desirable qualities and rapid growth on selected stems, but maintenance is lower than for other crop types. However, this reduces the growth rate of the entire forest community, because thinning invariably reduces leaf area. Dedicated energy crops also require management and harvesting; however, some dedicated energy crops do not require intensive management. The carbon storage potential for crops is determined by their life cycles and the level of human intervention.

Native hardwoods can be used to respond to the EPA new emission rule but they only provide a transitional solution. The hardwoods investigated for this report (i.e., oak, hickory, walnut, and maple) have relatively large crowns, so require a large area to grow and produce high-value lumber. Although their growth rates are slow in comparison to other crop types under consideration, the carbon they fix is stored for long periods of time because of how their wood is used (e.g., furniture-making and building materials). Using hardwood in place of metals, concrete, and plastics can reduce GHGs that are emitted during their manufacture. If credits for substitution are permitted, then the carbon effects of trees are as permanent as they can be. Furthermore, the trees add aesthetic value to areas where they are planted.

The economics for hardwoods is complicated. Rehabilitation of marginal lands (e.g., old mining sites) is one area where hardwoods can be utilized. Hardwood species require larger areas to grow than other biomass sources and the high cost of land may preclude their use for meeting sequestration goals. However, over time the tree can store more carbon than perennial crops and net increases in carbon fixation rates per unit area tend to be better. Policy changes may help offset some of these costs.

Because of the large area over which agricultural crops are grown, they have the potential to have great influence the global carbon cycle. Crop yields determine the amount of CO₂ fixed, with the yield dependent on factors such as nutrient and mineral content, harvest method, and climate. Agricultural land management practices can have negative impacts, but BMPs can help create favorable conditions for farmers (economically) and the environment. The largest sink for stored carbon is in the soil and the increasing concentrations of SOC have environmental benefits including higher yields, reduced soil erosion, and improved water filtration; however, the timeframe for such endeavors is longer than for other methods.
Yields and the potential of Indiana’s land for carbon sequestration are dictated by many factors, including the amount of land being used, the land management practices, and the properties of the soil. Thus, individual farms will have different yields and sequestration potentials, which are difficult to predict. Reduced tillage is increasing; more than half of Indiana’s soybean operations are using no-till practices. However, for corn the number of acres being conventionally tilled still outnumber those on which no-till and reduced tillage is being practiced. Conservation agricultural practices can lead to greater SOC and higher crop productivity and may be able to be included with some farmer’s practices of planting cover crops, because using agricultural crops for carbon sequestration has the advantage of an established infrastructure. Technological advances, including hybrids, have also led to higher yields. Hybrids have been developed for insect resistance, herbicide tolerance, reduced irrigation requirements, and earlier harvesting. However, depending on the farming practices, this does not mean greater carbon storage, and may lead to further SOC decreases.

When switching to conservation management practices, the economic opportunities for using stover as feedstock for biofuels are lost. Corn and soybean crops have been important feedstock in the production of biofuels; however, this diversion impacts the supply of food and feed. This has, in turn, increased the prices of products derived from these crops. In general, the SOC of agricultural cropland is lower than that of non-cultivated soils.

The use of dedicated energy crops is just beginning to occur at an operational scale. Hybrid poplars, Switchgrass, and Miscanthus have the advantage of not interfering directly with the food supply, because they are typically planted on land less suited for row crops. It is known that land-use change can have a domino effect. Although the crops cannot be used as food crops, the land they are produced on could be used to produce perennial forage crops that could be managed in rotation with no-till annual food crops. This is particularly true if the market price is high or policies promote production of them, growing these energy crops could displace some livestock forage/food crop production from the land and impact the food cycle. In addition, energy crops can be grown over a wide geographical range, and their energy content is greater than corn and soybeans. Dedicated energy crops also have: higher energy efficiencies, lower carbon footprints, and sequester more carbon than annual agricultural crops. They can also be used in power plants without having to drastically alter existing equipment.

The carbon cycle for the dedicated energy crops varies for poplar and perennial grasses (switchgrass and Miscanthus). The growth cycle for the poplar is similar to that of the other hardwoods discussed. The perennial grasses have a similar growth cycle to that of the agricultural crops, both of which are harvested only in the fall. In general, dedicated energy crops can be grown on small or large plots, produce high yields, do not require much maintenance, and need fewer inputs. Therefore, they have a high energy output/input ratio and lower carbon footprint. They also have environmental benefits associated with their use as biofuels, co-firing applications, or carbon storage. Their versatility makes them ideal for use on marginal lands and for remediating brownfield sites.

The economics of the dedicated energy crops varies by crop type. Switchgrass and Miscanthus can be established, maintained, and harvested using equipment similar that used with agriculture crops (albeit, with some challenges), while poplars may require different equipment for management activities, depending on their planting densities. As with hardwoods, the economics for the dedicated energy crops is complicated. The CRP provides a potential means by which
dedicated energy crops can be used to sequester carbon on land that may otherwise not be used, or else would be degraded.

States must act to meet EPA’s new CO₂ emission standards. This report presents a synthesis of information from a variety of sources without preference for any crop or strategy. Before adopting any of these strategies, a whole-system analysis must be conducted (i.e., biological and industrial energy inputs/outputs), including other environmental burdens. Although this report was prepared with Indiana and the Midwest in mind, the emission reductions needed to meet the new standards are a concern for all states. The goal is that this report will be a useful resource for a range of policymakers.

6.0 References


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