

# An overview: the potential role of agro forestry in enhancing carbon sequestration and reducing greenhouse gas emissions on agricultural lands

## Abstract

Agricultural production systems face major challenges under climate change scenarios in terms of expected negative impacts on productivity and persistence of the crops. Greenhouse gases from agriculture continue to rise although not as fast as from other fossil fuel-based human activities. Windbreaks perform several ecosystems functions that improve the local and regional capacity of crop systems to increase yields and offer environmental services by minimizing the negative effects of extreme weather events. Agro forestry systems also represent an important means of mitigating greenhouse gas emissions. This is predominantly accomplished by the trees and crops storing carbon (C) in their above and belowground woody tissue while reducing carbon dioxide (CO<sub>2</sub>) emissions either through avoidance of emissions or through energy savings. However, available and reliable data for estimating agro forestry contributions to whole-farm and regional C assessments are scarce and in most regions, do not exist. The main objective of this research was to analyze the C storage potential of agro forestry systems and to estimate the extent of potential reduction in emissions due to the presence of trees in different farming scenarios.

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## Introduction

Increasing levels of atmospheric greenhouse gases (GHGs) are triggering changes in our climate. In 2013, the Intergovernmental Panel on Climate Change<sup>1</sup> reported new and stronger evidence confirming that most warming observed over the last 50 years was attributable to anthropogenic causes. Climate change may impact society and ecosystems in a broad variety of ways.<sup>2,3</sup> There are conflicting perspectives about how to deal with the extent of its negative impacts. Dealing with these impacts requires countries around the world to reduce their atmospheric GHG emissions,<sup>4</sup> which in turn involves an enormous investment of capital and human resources, and a radical transformation of production systems and consumptive behavior.<sup>1,5</sup> Decision makers are discussing strategies to reduce GHG emissions. However, some strategies are not well received, and nothing is agreed upon by all nations.<sup>6</sup> In order to resolve this conflict, the world needs reliable tools to inform decision-makers, international negotiators, and public opinion about climate-change adaptation and mitigation management options.

Although the impact of the natural and anthropogenic perturbations on GHG emissions is permanent, future changes may be substantially reduced to safer levels.<sup>4,7</sup> Personal lifestyle changes that reduce the use of fossil fuels and reinforce sustainable farming can help minimize our C footprint. The Climate Smart Agriculture Approach<sup>5</sup> offers a set of practices to tackle atmospheric GHGs. Sustainable methods for managing GHGs in United States agricultural lands have been summarized in a CAST report (2011) and include: conservation, converting croplands to pasture, no till, reduced fuel use, forestation and reforestation. Agro forestry, the integration of woody plants into crops/livestock operations, is one of these methods. Since the Kyoto Protocol, agro forestry systems have gained more attention as a strategy to capture and store carbon (C).<sup>8,9</sup> The IPCC<sup>10</sup> reports that, "Agro forestry can both sequester C and produce a range of economic, environmental, and socioeconomic benefits." Consequently, integrating agro forestry onto the landscape is considered one of the best "no regrets" measures to help communities mitigate, adapt, and become resilient to the impacts of climate change.<sup>11</sup>

Despite agro forestry systems being recognized as a feasible tool to provide tangible and intangible goods and services while producing C services,<sup>12,13</sup> many gaps need to be filled to increase our understanding on how to best manage agro forestry for these services. These gaps can be addressed by increasing comprehensive scientific knowledge,<sup>14</sup> generating accurate and reliable data<sup>12,14,15</sup> unifying methodological approaches,<sup>6,14</sup> and evaluating their impacts on farming operations and C budgets.<sup>5,7,14</sup> Climate change presents a planet-wide experiment for researchers. There are many interventions under investigation. Integrating agro forestry practices on cultivated lands to tackle GHG emissions is one of them. Sound agro forestry research is the first step to understanding the factors related to climate change and how they will enhance the carbon storage potential for agricultural systems.

## Carbon cycle

The C cycle is the flux of C among the atmospheric, oceanic, terrestrial biosphere and geological deposits<sup>16,17</sup> which is stored in "carbon pools" (C stocks or reservoirs).<sup>18-20</sup> Within these pools, C flows from one source to another, transforming C from source to sink, and vice versa.<sup>21</sup> According to the United Nations Framework Convention on Climate Change, "A [C] source is any process or activity that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere; whereas a sink is any process, activity, or mechanism which removes C from the atmosphere".<sup>8</sup> Therefore, C sequestration is the capture and storage of C that would otherwise be emitted into the atmosphere.<sup>22,23</sup> Concentrations of carbon dioxide (CO<sub>2</sub>), a major cause of global warming, have increased at their fastest rate for the last 30 years.<sup>24</sup> The rise in CO<sub>2</sub> availability directly impacts photosynthetic processes evoking a wide range of physiological and morphological responses in plants.<sup>25,26</sup> It is believed that most woody plants can produce more biomass at an elevated CO<sub>2</sub> concentration,<sup>27-33</sup> however, many uncertainties remain about which tree species will benefit or be constrained at that concentration because the benefits of "growth" may be more appealing to pest or diseases.<sup>34-36</sup>

Based on photosynthetic physiology, it is likely that the additional

C uptake beyond a threshold will limit the plant's ability to effectively uptake CO<sub>2</sub>.<sup>25</sup> Additionally the capacity of surface waters to take up anthropogenic CO<sub>2</sub> is decreasing as levels increase. These phenomena make concentrations of CO<sub>2</sub> more sensitive to natural and anthropogenic emissions.<sup>1</sup> Many uncertainties remain and more research is needed to define the effect of natural sinks in the further reduction of CO<sub>2</sub>. Given this situation, mitigation and adaptation strategies aimed to address these challenges are being proposed. Mitigation strategies tackle the causes of climate change and adaptation attacks the effects of the climate change on humans and ecosystems.<sup>4</sup> Jacoby et al.,<sup>37</sup> define mitigation as actions that reduce human contributions of GHGs to the planet. IPCC<sup>4</sup> states that adaptation is the process of adjustment to actual or expected climate and its effects. Mitigation measures include lowering emissions of GHGs (CO<sub>2</sub>, NO<sub>2</sub>, and CH<sub>4</sub>) and increasing the net uptake of CO<sub>2</sub> through land-use changes, like forestry. These environmental threats can be mitigated if excess C is removed from the atmosphere, but according to the National Climate Assessment,<sup>38</sup> "Natural processes only remove roughly half of the current rate of emissions from human activities. Therefore, mitigation efforts that only stabilize global emissions will not reduce the overall atmospheric concentrations of C, but will only limit the rate of the increase. The same is true for other long-lived greenhouse gases." All of these statements indicate that humans have a significant role to play in addressing climate change. Their intervention is needed to reduce GHG emissions to safer levels and to stabilize the C cycle through C storage.

### Direct carbon storage

Direct C storage refers to a set of processes designed to capture CO<sub>2</sub> from the atmosphere, and then store it in either woody material or in other more stable fractions, such as in soils or geological formations.<sup>9</sup> Lal<sup>39</sup> identified four direct C sinks:

- i. Forestation, where CO<sub>2</sub> is removed from the atmosphere via biological activity;
- ii. Aquifer storage, where CO<sub>2</sub> is injected into terrestrial aquifers and is trapped hydro-dynamically;
- iii. deep-sea storage, where CO<sub>2</sub> is injected into the ocean at approximately 3,000m., where it is believed to remain stable for the long term; and
- iv. Mineral carbonation, in which the CO<sub>2</sub> reacts with minerals to form solid carbonates.

The focus of this dissertation is on the first phenomenon, carbon storage by via plants. Here, direct plant C sequestration takes place when plants photosynthesize atmospheric CO<sub>2</sub> and store it as plant biomass. Subsequently, in forestation (tree-based) activities some of this plant biomass is fixed in woody materials while other biomass is indirectly sequestered as soil organic carbon (SOC) during decomposition processes.<sup>40-42</sup> The accumulation of C fixed through agronomic, forestry, and conservation practices ultimately leads to a net gain in C fixation in soils.<sup>41</sup> Biological uptake and storage in woody plant material is one way to mitigate GHG emissions.<sup>8</sup> In temperate zones, sustainable agriculture, reforestation, a forestation, and agro forestry systems (AFS) represent potential C sinks.<sup>14,41,43-46</sup>

### Avoided C emissions or indirect C storage

Avoided or reduced emissions refer to the estimate of C equivalent emissions that could have been released if a particular activity or intervention had not been carried out.<sup>47-49</sup> In agriculture, these

avoided emissions result from the reduced use of energy for planting and growing a crop; producing and using fertilizers and pesticides, clearing roads of snow during winter, and heating and cooling homes.<sup>50</sup> Any practice that reduces the amount of fossil fuel usage will result in avoided CO<sub>2</sub> emissions.<sup>2</sup> Emissions avoidance is the most effective C management strategy to achieve atmospheric CO<sub>2</sub> stabilization and a subsequent decline of atmospheric CO<sub>2</sub>.<sup>51</sup> Energy efficiencies through reduced energy consumption, renewable energy use, cleaner energy production, and switching to fuels with lower carbon contents are current strategies to reduce CO<sub>2</sub> emissions.<sup>3</sup>

Trees and wood waste are also being used as alternative sources of energy. Biomass from trees is suitable to produce heat, power, and transportation fuels.<sup>52</sup> Net CO<sub>2</sub> emissions from a unit of electricity generation from bio-energy are 10 to 20times lower than from fossil fuel based electricity generation.<sup>52</sup> Incorporating trees into the farm system provides additional benefits. Field windbreaks result in fewer acres being farmed which means a reduction in fuel consumption and a reduction of C emissions.<sup>43</sup> Fewer acres farmed reduce fertilizer and pesticide inputs, thus reducing the off-farm carbon impact.<sup>43</sup> Trees around buildings, rural and urban homes reduce the amount of fossil fuel required for heating and cooling.<sup>43,50,53-55</sup> Depending on climatic zone; building size, structure and age; and the type of energy consumed protecting these structures can provide significant savings.<sup>43</sup>

### The role of agriculture in contributing to GHG production and mitigation

Agriculture has been identified as one of the anthropogenic activities that produce substantial amounts of GHGs.<sup>56,57</sup> Burning fossil fuels is the leading cause of anthropogenic GHG emissions into the atmosphere in the form of CO<sub>2</sub>.<sup>58</sup> Besides emitting CO<sub>2</sub>, the rate of methane (CH<sub>4</sub>) emissions from farming operations has doubled over the last 25years, increasing at a rate of 1% per year<sup>59</sup> with 70 - 90% coming from biotic sources.<sup>60</sup> Atmospheric concentrations of nitrous oxide (N<sub>2</sub>O) are reported to have increased from 270 ppb during the preindustrial era to 325 ppb in 2014.<sup>2</sup> At the global, regional, and local scale, agriculture is considered the largest source of anthropogenic N<sub>2</sub>O and CH<sub>4</sub>,<sup>61</sup> contributing 52% of global methane and 84% of global nitrous oxide emissions.<sup>62</sup> Agricultural systems continue to add C to the atmosphere by using fossil fuels in machinery, using chemicals and other inputs that are energy intensive to manufacture, and cultivating soil, which results in a dynamic release of C.<sup>22,39,63</sup> A global analysis of soil C loss following cultivation of forests or grasslands shows a 20% reduction of the initial soil organic carbon (SOC), or approximately 1,500gm<sup>-2</sup> in the top 0.3m of the soil.<sup>64</sup> Davidson & Ackerman<sup>65</sup> estimated 30% SOC loss within 20years following cultivation, with the greatest loss in the first 5years. Conversely, agriculture is also an accumulator of C; offsetting losses when the organic matter (OM) accumulates in the soil or when aboveground woody biomass acts either as a semi-permanent sink or is used as an energy source.<sup>39,63,66-69</sup>

Long-term rates of C storage are reported in different agro ecosystems ranging from a low of 0.2 g C m<sup>-2</sup> yr<sup>-1</sup> in some polar deserts to more than 10 g C m<sup>-2</sup> yr<sup>-1</sup> in some forest ecosystems.<sup>70</sup> Most agro ecosystems have the potential to store C. Pastures, agro forestry and forest ecosystems tend to lead in soil C storage, depending on the region. In some regions, large agricultural areas represent a considerable potential for enhancing the rate of C sequestration through management activities that reverse the effects of cultivation on soil organic carbon (SOC) pools.<sup>71</sup> In these cases, refilling depleted soil C pools via woody biomass production may result in much higher rates of SOC storage than the accumulation of passive soil C

as documented by Schlesinger.<sup>70</sup> These results suggest that enhancing the transfer of atmospheric C into soil using specific soil management practices may help mitigate climate-change impacts. However, this concept only applies when the additional C remains stored and is not rapidly released.<sup>68,72</sup> For this reason, it is essential to estimate the duration of storage or mean residence time (MRT) of C in agricultural soils.<sup>73</sup>

### Building a climate smart agriculture

Addressing the global challenges of climate change, food security, and poverty alleviation requires enhancing the adaptive capacity and mitigation potential of agricultural landscapes throughout the world.<sup>74</sup> Agriculture must simultaneously address three interwoven challenges: food security, adaptation to climate change, and mitigation of climate-change impacts.<sup>5,75,76</sup> The Climate Smart Agriculture (CSA) approach was proposed by FAO<sup>5</sup> as a strategy to tackle these social and environmental challenges. Climate Smart Agriculture is defined as the integration of the three dimensions of sustainable development to address food security and climate challenges: social, economic, and environmental.<sup>5</sup> Several management strategies hold particular promise for simultaneously achieving these three goals of production, adaptation and mitigation at the plot and farm scale.<sup>77</sup> For example, soil conservation practices, such as conservation tillage can increase soil health and protect the soil from extreme weather events.<sup>78</sup> Many “climate-smart” practices that address both adaptation and mitigation goals are already well-known and fall under the greater umbrella of conservation agriculture, agro forestry, sustainable agriculture, evergreen agriculture, silvo pastoral systems, sustainable land management, eco-agriculture, or best-management practices.<sup>5,79</sup> Still, a greater understanding of these practices and their adoption rate is required to produce reliable information and technologies that land managers will embrace.<sup>77</sup>

### The role of agro forestry systems in the climate smart agriculture approach

Agro forestry systems (AFS) are defined as technologies where woody perennials (trees, shrubs, palms, and bamboos) are deliberately grown on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence.<sup>8,80</sup> Integrating woody plants into crop and livestock systems, if properly designed and located, can improve soils, increase water and air quality, and enhance wildlife habitat, while at the same time supporting sustainable production.<sup>81</sup> While agro forestry plays a significant role in mitigating the concentration of GHGs, it also helps farmers to adapt to climate change.<sup>82,83</sup> For these reasons, agro forestry is included as a management option for C sequestration under the Clean Development Mechanisms of the Kyoto Protocol<sup>19,84,85</sup> and CSA approach.<sup>5</sup> In North America, there are five main categories of agro forestry practiced: riparian forest buffers, windbreaks, alley cropping, silvo pasture, and forest farming. These categories vary according to the structure and function of their components. By incorporating agro forestry practices into agricultural operations, the amount of C that can potentially be sequestered is greater than that achievable by crops alone.<sup>86,87</sup> At a global scale this potential ranges from 0.29 to 15.21Mg ha<sup>-1</sup> yr<sup>-188</sup> while conservation practices on croplands in the United States range from 0.1<sup>89</sup> to 2.15 Mg ha<sup>-1</sup> yr<sup>-1</sup>.<sup>90</sup> The greatest dividend of C sequestered via agro forestry practices comes from the increased soil organic carbon (SOC) belowground and the woody biomass, above- and belowground.<sup>8,91</sup>

Although C sequestration through afforestation and reforestation has long been considered useful in climate-change mitigation,<sup>8</sup> agro forestry offers distinct advantages. Agro forestry practices enhance the capability of farmers to increase soil health, improve air and water quality, increase local biodiversity, reduce weeds and pests, reduce pressure on natural forests, and enhance welfare for livestock.<sup>43,92–95</sup> Likewise, these systems can enhance the resilience of farms coping with extreme events.<sup>82,83</sup> Agro forestry, when used to intensify agriculture production, provides additional indirect benefits by: 1) reducing the farm’s use of fossil fuels, 2) reducing the energy used for heating and cooling homes and other buildings, 3) reducing the inputs applied to crops and livestock, and 4) providing more diversity for wildlife habitat.<sup>43,63,96</sup> Likewise, diversifying the crop production system to include a significant tree component may buffer the income risks associated with climatic variability.<sup>82</sup>

Globally, agro forestry offers important opportunities to create synergies between adaptation and mitigation actions.<sup>5</sup> Simulation models developed to evaluate the potential of agro forestry practices to store C suggested that there are approximately 85 to 1,215 M ha in agro forestry practices in Africa, Asia, and the Americas.<sup>97</sup> The IPCC projected that 630 M ha of unproductive cropland and grassland could be converted to agro forestry by 2010<sup>8</sup> and could potentially sequester 1.43 and 2.15Tg CO<sub>2</sub> yr<sup>-1</sup> by 2010 and 2040, respectively. Kumar et al.,<sup>98</sup> estimated that 1,023 M ha are currently under agro forestry worldwide. The global potential to sequester C was estimated at 1.1 to 2.2Gt (1Gt=1,000Tg) of C per year over 50 years.<sup>97</sup> Using values and total land area planted to agro forestry (1,215M ha) from Dixon<sup>97</sup> a C sequestration potential of 1.9 x10<sup>3</sup>Tg C yr<sup>-1</sup> over 50years was calculated.<sup>99</sup> These estimates are close to the 1.6 to 1.8 x 10<sup>3</sup>Tg C yr<sup>-1</sup> lost due to deforestation and other agricultural activities.<sup>100</sup> However, in order to increase the amount of C sequestration and contribute effectively to atmospheric CO<sub>2</sub> reduction, new agro forestry projects must be implemented on the remaining 3,953M ha of cropland and pastures in the world.<sup>99</sup>

In North America, potential C sequestration rates of AFS for above- and belowground biomass components were estimated at 2.6Mg C ha<sup>-1</sup> yr<sup>-1</sup> for riparian forest buffers, 3.4 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for alley-cropping systems, 6.1Mg C ha<sup>-1</sup> yr<sup>-1</sup> for silvo pastures, and 6.4 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for windbreaks.<sup>6</sup> Additionally, 630 M ha of unproductive croplands and grasslands could be converted to agro forestry, representing a C sequestration potential of 0.4Tg C yr<sup>-1</sup> by 2010 and 0.6Tg C yr<sup>-1</sup> by 2040.<sup>19,101</sup> These estimates were derived from 1.69 M ha under riparian buffers, 17.9 M ha (10% of total cropland) in alley cropping, and 78 M ha of silvopasture (23.7 M ha or 10% of pasture land, and 54 M ha of grazed forests).<sup>6,14</sup> These systems have the potential to store 4.7, 60.9, 474 and 8.79 to 58Tg C yr<sup>-1</sup>, respectively.<sup>6</sup> Estimates of the C storage potential for agro forestry systems are shown in Table 1. Although there is little doubt about the potential of agro forestry to store C, their effectiveness is determined by local physical, ecological, and socio-economic factors.<sup>14,102</sup> Locally, the amount of C in any agro forestry system depends on the structure and function of different components within the specific system.<sup>103,104</sup> The interaction among these factors generates high levels of spatial heterogeneity among similar agro forestry practices at different locations.<sup>91</sup> Therefore, extrapolation across systems and locations can be misleading when applying local results on a global scale.<sup>91,105,106</sup>

As with all agricultural management activities, agro forestry systems can function as both a source and sink of GHG.<sup>6,15,91,97</sup> Evidence from Dixon<sup>97</sup> Chikowo et al.,<sup>107</sup> Kandji et al.,<sup>108</sup> suggests that the type

of agro forestry system greatly influences whether the components function as a source or sink and to what extent. For instance, Dixon<sup>97</sup> Chikowo et al.,<sup>107</sup> Kandji et al.,<sup>108</sup> show improved fallows and silvo pastures as sources of NO<sub>2</sub> and CH<sub>4</sub>, respectively. However, the net C equivalent in the aboveground and belowground biomass of an agro forestry system is generally much higher than the equivalent land use without trees<sup>12,44,94,109</sup> see Table 1. In the case of riparian forest buffers in agricultural systems, these plantings can reduce excess NO<sub>2</sub> emissions through the uptake of N by trees.<sup>110</sup> reduce the impacts from flood events,<sup>111</sup> store C, prevent nutrient losses, and reduce erosion.<sup>112</sup> Similarly, planting bio fuel crops on arable lands can potentially reduce nitrate losses<sup>113</sup> and soil erosion.<sup>114,115</sup> Incorporating a bio feed

stock component into riparian buffer systems, where appropriate, can provide farmers with additional income as well as provide added GHG mitigation and water quality services.<sup>83</sup> Inventory data and field measurements of agro forestry within the US, and more broadly North America, are very limited.<sup>116</sup> Carbon sequestration estimates reported above were made using a variety of broad assumptions. The inherent variability of C storage potential and the lack of uniform methodologies among the many estimates make statistical comparisons challenging.<sup>101,109</sup> Despite these difficulties, trends from the information at hand indicate that AFS will sequester C and favorably reduce CO<sub>2</sub> emissions.<sup>12,13,15,106,117</sup>

**Table 1** Worldwide carbon storage potential of agro forestry systems

Agroforestry/land-use system	Years	Carbon storage (Mg ha <sup>-1</sup> yr <sup>-1</sup> )	Source
Fodder bank, Segou (Mali W African Sahel)	7.9	0.3	Takimoto et al., <sup>187</sup>
Live fence, Segou (Mali, W African Sahel)	-	0.6	Takimoto et al., <sup>187</sup>
Tree-based intercropping (Canada)	13.0	0.8	Peichl et al., <sup>188</sup>
Parklands, Segou, Mali (W African Sahel)	35.0	1.1	Takimoto et al., <sup>187</sup>
Agrisilviculture (Chattisgarh, central India)	5	1.3	Swamy & Puri <sup>189</sup>
Silvopasture (W Oregon, USA)	11	1.1	Sharrow & Ismail <sup>190</sup>
Cacao agroforests (Mokoe, Cameroon)	26	5.9	Duguma et al., <sup>191</sup>
Cacao agroforests (Turrialba, Costa Rica)	5	10.3	Beer et al., <sup>192</sup>
Cacao agroforests (Turrialba, Costa Rica)	10	11.1	Beer et al., <sup>192</sup>
Shaded coffee (SW Togo)	13	6.3	Dossa et al., <sup>193</sup>
Agroforestry woodlots (Kerala, India)	5	6.6	Kumar et al., <sup>194</sup>
Home and outfield gardens	23.2	4.3	Kirby & Polvin <sup>195</sup>
Indonesian home gardens, (Sumatra)	13.4	8.0	Roshetko et al., <sup>196</sup>
Mixed species stands, (Puerto Rico)	-	621	Parrotta <sup>197</sup>
Agroforestry systems (world)	50	1.7	IPCC <sup>22</sup>
Agroforestry systems (World)	50	1.9	Dixon et al., <sup>97</sup>
Agroforestry systems (world)	-	0.7	Eagle et al., <sup>15</sup>
Agroforestry systems (world)	-	0.2 - 4.6	Krankina & Dixon <sup>198</sup> Schroeder <sup>103</sup> Winjum et al., <sup>199</sup> Pandey <sup>200</sup>
Agroforestry slow growing trees (Europe)	-	0.1 – 0.57	Palma et al., <sup>201</sup>
Agroforestry mod. fast growing trees (Europe)	-	0.54 – 0.9	Palma et al., <sup>201</sup>
Agroforestry fast growing trees (Europe)	-	2.1 – 3.0	Palma et al., <sup>201</sup>
Agroforestry systems (tropical)	-	1.5 – 3.5	Montagnini & Nair <sup>91</sup> Watson et al., <sup>84</sup>
Agroforestry systems (tropical)	-	3.1 – 4.3	Beer <sup>192</sup>
Agroforestry (USA)	-	0.22 – 1.88	Eagle et al., <sup>15</sup>
Riparian buffer/mile (USA)	40	5.01 – 10.03	Schoeneberger <sup>12</sup>
Riparian buffer/mile (USA)	-	1.8	Hazlett et al., <sup>202</sup>
Riparian buffer (USA)	-	1.87	Nair & Nair <sup>14</sup>
Riparian buffer/mile (USA)	-	4.8	Rheinhardt et al., <sup>203</sup>
Agroforestry (USA)	-	0.72	Dixon et al. <sup>97</sup>

Table Continued

Agroforestry/land-use system	Years	Carbon storage (Mg ha <sup>-1</sup> yr <sup>-1</sup> )	Source
Alley cropping (USA)	-	2.4 – 3.4	Udawatta & Jose <sup>6</sup>
Alley cropping (USA)	-	4.5	Nair & Nair <sup>86</sup>
Alley cropping (USA)	-	1.15	Nair & Nair <sup>14</sup>
Alley cropping (USA)	-	1.15	Lal et al., <sup>89</sup>
Alley cropping (USA)	-	0.5 – 13.2	Bambrick <sup>204</sup>
Silvopasture (USA)	-	6.1	Udawatta & Jose <sup>6</sup>
Silvopasture (USA)	-	5 – 10.1	USDA-NAC <sup>148</sup>
Silvopasture (USA)	-	0.3	Nair & Nair <sup>14</sup>
Silvopasture (USA)	-	2.6	Nair & Nair <sup>14</sup>

Source adapted from Nair et al.,<sup>86</sup>

As one of several promising climate-change mitigation and adaptation tools that will be needed for agricultural lands under the uncertainty of climate change<sup>7</sup> implementing agro forestry projects is justified for many reasons. First, an increase in soil C significantly benefits agricultural productivity and sustainability.<sup>82,86,118–120</sup> Second, it is improbable that any single mitigation method can achieve CO<sub>2</sub> reduction targets, rather combining several management activities, including the perennial-based agro forestry practices, appears to be a more realistic way to achieve CO<sub>2</sub> reduction targets, especially under the uncertainties of climate change.<sup>106,121</sup> Third, as the sale of C through Clean Development Mechanisms (CDM) becomes more popular in the future, agro forestry systems will definitely have potential to provide economic revenue for farmers while working to improve the environment, especially in developing countries.<sup>122</sup> Integrated analysis of agro forestry shows that these systems can sequester C and potentially increase incomes of farmers around the world.<sup>123</sup>

### Windbreaks/shelterbelts

Temperate agro forestry systems in North America encompass five categories of practices as cited in Table 1.<sup>124</sup> Windbreaks (also referred to as shelterbelts) are particularly attractive as a GHG mitigation tool for C storage in agricultural lands.<sup>12</sup> This is because windbreaks take only a small portion of land out of production (3–5%),<sup>124</sup> yet provide many other services that are valued by the landowner and society, such as enhanced production to make up for the land taken out of production, along with the co-benefits of C sequestration and avoided emissions.<sup>12</sup> Windbreaks are linear arrays of trees and shrubs<sup>125</sup> that serve as barriers to reduce wind speed.<sup>124,126</sup> They usually consist of one or more rows of trees or shrubs planted on croplands or grazing lands to alter the local microclimate<sup>124,127</sup> protect crops and livestock,<sup>124</sup> provide habitat for wildlife<sup>128,129</sup> and mitigate odors from farming operations.<sup>130</sup> Windbreaks reduce evapotranspiration<sup>124,131</sup> wind erosion, and soil detachment by rain drops.<sup>43</sup> They supply additional C sequestration in crop and livestock production systems, and increase energy savings in farm operations by reducing the amount of fossil fuel required to heat and cool homesteads and barns.<sup>43,52</sup> Table 2 presents a review of studies that include a range of experimental designs, building types, landscaping, and climate conditions where energy savings for space heating and cooling ranged from 8%<sup>53</sup> to 50%.<sup>54</sup>

Conservative energy savings ranging from 10 to 25% reported by USDA<sup>132</sup> need to be re-evaluated due to the technological advances in

heating and cooling systems, home insulation, appliance types, and the concerns about climate change. This value, however, is close to the estimate of Moyer<sup>133</sup> in Saskatchewan (Canada). Other studies have examined urban tree plantings and found similar ranges in cooling savings from well-placed trees ranging from 10 to 43%.<sup>134</sup> Living snow fences are windbreaks planted to manage drifting snow. Depending on the design, living snow fences can reduce snow removal costs from adjacent roadways and improve road safety by trapping snow close to the shelterbelt<sup>135–138</sup> or provide critical spring soil moisture for crops during the growing season by distributing snow relatively uniformly across a field.<sup>139</sup> Incorrectly designed and placed windbreaks, on the other hand, can cause snowdrifts that can bury livestock during major storms.<sup>140</sup> There are many reviews of windbreak performance in different scenarios around the world and the reader is referred to these for specific details on the functions of windbreaks.<sup>6,15,43,131,141–146</sup> Windbreaks have the most impact in semiarid areas where a major function is to protect soils from wind erosion.<sup>143</sup> The largest and most extensive shelterbelt-planting program in United States history was “the Prairie States Forestry Project.” In an effort to control the dust bowl the Federal Government initiated the planting of nearly 30,000km of shelterbelts in six Great Plains States between 1935 and 1942.<sup>147</sup> Today, the growth and vigor of many of these trees have declined due to lack of management, spacing, aging, and invasion of undesirable, short-lived trees. Many others have been removed to accommodate various types of irrigation systems particularly center pivot systems. As climate change concerns continue to rise, especially in regards to frequency and intensity of droughts, there is a renewed interest in windbreaks as both protection against wind erosion and as potential C sinks. Estimates of C sequestration by windbreaks are shown in Table 3. Most of these estimates are based only on the aboveground portion for different shelterbelt types in the United States and Canada. These estimates ranged from 0.68Mg C km<sup>-1</sup> for single-row shrubs<sup>43</sup> to 105Mg C km<sup>-1</sup> for single row hybrid poplar (*Populus deltoides* x *Populus nigra* Bartr. Ex. Marsh).<sup>55</sup>

Windbreaks contribute to the SOC pool, although at a limited spatial scale of the landscape.<sup>6</sup> Sauer et al.,<sup>105</sup> reported SOC concentrations under a Nebraska shelterbelt to be 55% more than that in the adjacent crop field. The shelterbelt treatment contained 12% more SOC in the 7.5–15cm depth compared to the crop field. Overall, during a 35-year period, soils at 0–15cm depth contained 3.71Mg more SOC ha<sup>-1</sup> in the shelterbelt area than the cultivated zone, which according to Udawatta & Jose<sup>6</sup> can represent an annual sequestration

of 0.11Mg ha<sup>-1</sup>. Hernandez & Ramirez<sup>119</sup> indicated that a forestation of cropland carried out through either shelterbelt or forest plantation caused substantial increases in SOC accrual (≥57%) in surface soil layers (to 7.5 or 10cm deep) relative to conventionally, tilled cropping systems.

**Table 2** Effects of windbreaks on energy savings in the United States and Canada

House type	Place	Energy demand Kw h <sup>-1</sup>	Energy savings(%)	Author
Heavily shaded house	Sacramento	0.61 – 4.8	25 – 50	Akbari et al., <sup>54</sup>
Houses with air conditioner	Phoenix	0.17	17	Clark & Berry <sup>205</sup>
Houses with air conditioners and evaporative coolers	Phoenix	0.35	14	Clark & Berry <sup>205</sup>
House without trees		3.55	-	Clark & Berry <sup>205</sup>
Simulation for Cities	U.S.	0.15 – 0.5	2 – 10	Heisler, <sup>206</sup> Huang et al., <sup>207</sup> McPherson <sup>134,208</sup>
Average House	Great Plains	-	23 - 25	Bates <sup>209</sup>
Average House	U.S.	-	27	USDA-NRCS <sup>132</sup>
Average House	Kansas	-	15	Woodruff <sup>210</sup>
Average House, single row windbreak		-	40	Mattingly <sup>53</sup>
Air conditioning reduction	New Jersey	-	8	Mattingly et al., <sup>53</sup>
Heating	New Jersey	-	3	Mattingly et al., <sup>53</sup>
Air conditioning reduction	New Jersey	-	10	Harrje et al., <sup>211</sup>
Heating energy	New Jersey	-	3	Harrje et al., <sup>211</sup>
Heating energy	Pennsylvania	-	12	DeWalle & Heisler <sup>50</sup>
Heating	Pennsylvania	-	0	Walk et al., <sup>212</sup>
Typical northern US farm		-	10 – 30	DeWalle & Heisler <sup>50</sup>
Wind speed reduction	Canada	-	17 – 25	Moyer <sup>133</sup>
Urban home cooling		-	10 - 43	McPherson <sup>134</sup>

**Table 3** Estimates of carbon storage potential for windbreaks/shelterbelts

Agroforestry/land-use system	Years	Carbon storage Mg	Carbon storage Mg km <sup>-1</sup>	Source
Aboveground deciduous trees (Canada)	-	0.11- 0.367	105	Kort & Turnock <sup>55</sup>
Aboveground coniferous trees (Canada)	-	0.11– 0.19	24- 41	Kort & Turnock <sup>55</sup>
Aboveground shrub (Canada)	-	-	11	Kort & Turnock <sup>55</sup>
Green ash (Canada)	53	0.161.8	32	Kort & Turnock <sup>55</sup>
Austrian pine (U.S.)	1	0.004	-	Sampson & Kamp <sup>213</sup>
Eastern red cedar(U.S.)	1	0.0015	-	Sampson & Kamp <sup>213</sup>
Manitoba maple (Canada)	52	0.178.6	34	Kort & Turnock <sup>55</sup>
Hybrid poplar (Canada)	33	0.544.3	105	Kort & Turnock <sup>55</sup>
Hybrid poplar (Canada)	13	0.12	-	Peichl et al., <sup>188</sup>
Hybrid poplar/tree/roots (Canada)	12	0.02	-	Gordon & Thevathasan <sup>96</sup>
Poplar (Canada)	25	0.03	-	Wotherspoon et al., <sup>214</sup>
Red oak (Canada)	25	0.03	-	Wotherspoon et al., <sup>214</sup>
Walnut (Canada)	25	0.023	-	Wotherspoon et al., <sup>214</sup>

Table Continued

Agroforestry/land-use system	Years	Carbon storage Mg	Carbon storage Mg km <sup>-1</sup>	Source
Norway spruce (Canada)	25	0.03	-	Wotherspoon et al., <sup>214</sup>
White cedar (Canada)	25	0.02	-	Wotherspoon et al., <sup>214</sup>
Siberian elm (Canada)	37	0.201.9	40	Kort & Turnock <sup>55</sup>
White spruce (Canada)	54	0.286.9	41	Kort & Turnock <sup>55</sup>
Scots pine (Canada)	66	0.164	24	Kort & Turnock <sup>55</sup>
Colorado spruce (Canada)	43	0.202	29	Kort & Turnock <sup>55</sup>
Choke cherry (Canada)	33	0.403	20	Kort & Turnock <sup>55</sup>
Villosa lilac (Canada)	23	0.335	17	Kort & Turnock <sup>55</sup>
Buffalo berry (Canada)	20	0.312	15	Kort & Turnock <sup>55</sup>
Above-ground single row conifer (Nebraska-USA)	20	-	9.14	Brandle et al., <sup>43</sup>
Caragana (Canada)	49	0.516	26	Kort & Turnock <sup>55</sup>
Sea buckthorn (Canada)	25	0.213	11	Kort & Turnock <sup>55</sup>
Aboveground single row deciduous (Nebraska-USA)	20	-	5.41	Brandle et al., <sup>43</sup>
Aboveground single row shrub conifer (Nebraska-U.S.)	20	-	0.68	Brandle et al., <sup>43</sup>
Hybrid poplar (Canada)/km	-	-	105	Kort & Turnock <sup>55</sup>
Sea buckthorn/km	-	-	11	Kort & Turnock <sup>55</sup>
Conifer	-	-	24 – .41	Kort& Turnock <sup>55</sup>
Green ash	-	-	0.32	Kort & Turnock <sup>55</sup>
Two rows shelterbelt soil organic carbon 15 cm depth (Nebraska U.S.)/ha	35	39.94	-	Sauer et al., <sup>105</sup>
Hypothetic windbreak Sounders, Nebraska/ha		2.95	-	Schoeneberger <sup>184</sup>
Soil organic Carbon 0 to 0.075m/ha	36	23.1	-	Brandle et al., <sup>124</sup>
Soil organic Carbon 0.075 to 0.15m/ha	36	16.8	-	Brandle et al., <sup>124</sup>

This increase of SOC in the shelterbelt is attributed to the absence of soil disturbance, increased litter accumulation, reduced erosion, and deposition of windblown material.<sup>107</sup> Further research is needed to identify the mechanism (s) responsible for the observed patterns of SOC within and adjacent to the shelterbelt, and to quantify the C in biomass and deeper soil layers.<sup>107</sup> Overall, the estimated C storage potential of different scenarios of windbreaks in the United States ranges from 2.9 to 11Tg C ha yr<sup>-1</sup>.<sup>6,14,43,91,148</sup> According to the scientific body of research on agro forestry, windbreaks are a practical way to store C on agricultural lands, but many questions remain. As pointed out by Schoeneberger et al.,<sup>83</sup> the spatial and temporal dynamics in the system require additional research and technology investment. Few papers have been written about C stocks in trees on cultivated lands.<sup>105</sup> Windbreaks lack explicit inclusion in any national inventory<sup>116</sup> making it difficult to accurately estimate the land area occupied by this practice and therefore its C storage potential.

### Moving farming systems towards carbon neutral farming

Integrated farming systems (or integrated agriculture) refer to agricultural systems that incorporate crops, domestic animals,

trees, and non-conventional farming operations through nutrient cycling.<sup>149–153</sup> The farm is conceived as a holistic or multi-functional land unit planned to maximize farm production and increase welfare of farm families<sup>150,152</sup> while at the same time improving the environment. Integrating crops, livestock, and trees on farming operations is an agronomic, economic, and environmental challenge because of the complex interactions between components.<sup>154</sup> Under holistic management, these types of production systems can achieve a more favorable net C footprint through crop residues, animal manures, soil conservation practices, crop rotations using intercropping and cover crops, and composting techniques.<sup>155</sup> Studies in the United States show that alternative farming systems can achieve net returns comparable to those of conventional farms.<sup>156–158</sup> While yields are usually somewhat lower, alternative farms often compensate by lower input costs and greater net returns.<sup>156,157,159</sup> Studies comparing organic and conventional grain production systems show organic farming to be more sustainable.<sup>156,157,159–168</sup>

Soil tillage, planting, and harvesting operations account for the greatest expenditure of fuel, labor, and input costs.<sup>169</sup> Approaches to decrease these expenses are reduced soil tillage,<sup>170</sup> optimized fertilizer utilization and use efficiency,<sup>171</sup> improved irrigation techniques, and

enhanced solar drying. Likewise, considerable energy savings can come from intensive animal husbandry.<sup>1,172</sup> Cole et al.,<sup>171</sup> Paustian et al.,<sup>121</sup> optimistically concluded that by integrating all of these possibilities, a 10 to 40% reduction in the current agricultural energy requirements might be achieved. Accordingly, theoretical U.S. fuel savings could be 0.01 to 0.05Gt Cyear.<sup>121</sup> When trees are planted as agro forestry plantings on farms, the net GHG emissions in terms of C equivalents (CE) are substantially reduced. For a hypothetical farm of 250ha, in Nebraska, the CO<sub>2</sub> sequestered under two management options (no-till with and without windbreaks) were estimate after 50years to be 9.2Gt under just no-till and 16.1Gt under no-till with 5% of the land in windbreaks (the level of windbreaks generally prescribed for providing a good level of crop services).<sup>12</sup> Farming systems that include agro forestry create more complex and productive units. Choosing a set of best practices involves more than simply identifying practices to reduce emissions or those that make immediate economic sense. A more holistic farming approach includes: finding ways to understand and quantify the diverse services provided to farms by windbreaks, developing new ways to better quantify C balance on farms, and improving methods to compare practices on the basis of emissions per unit of output, rather than merely based on emissions by unit of area. Many methods and tools are needed.

Estimating the amount of emissions and potential of C storage on integrated farms is a challenging task and research in this field is still in its early stages. However, some advanced decision-support tools can facilitate research and reduce the investigation time. The combination of these tools and other data from different sources can play an important role in furthering the understanding necessary to conduct more comprehensive agro forestry research. Deneff et al.,<sup>173</sup> have reported on several science-based methods for quantifying GHG sources and sinks in agriculture and forestry. Decision-support tools to easily and accurately assess potential C contributions of agro forestry practices on farms are: Soil Changes under Agro forestry (SCUAF),<sup>174</sup> COMET-VR 2.0,<sup>175</sup> USAID FCC: Agro forestry tool,<sup>176</sup> Integrated Farming Systems (IFSM),<sup>177</sup> COMET-Farm,<sup>178</sup> and HOLOS.<sup>179</sup> Currently, some of these tools enable users to estimate C storage on farms with and without agro forestry systems, although these estimates are not without issue regarding accuracy.

COMET-Farm (<http://cometfarm.nrel.colostate.edu/>) is currently an entity-level, user-friendly tool for estimating the amount of C stored on agro forestry farms in the United States. This program places a value on a farm's C storage and under alternative management scenarios, including agro forestry. Amounts are then reported regarding GHG emissions between current management and future scenarios.<sup>178</sup> HOLOS ([www.agr.gc.ca/holos-ghg](http://www.agr.gc.ca/holos-ghg)) estimates whole-farm GHG emissions and carbon storage from lineal tree plantings. And finally, another user-friendly tool for estimating GHGs is IFSM (<http://www.ars.usda.gov/services/software/download.htm?softwareid=5>) which includes livestock, but it does not include agro forestry practices. Overall, there is a high potential for windbreaks to help farm operations tackle the negative effects of climate change. Windbreaks can enhance the ability of farmers and agro ecologists to deal with the uncertainties of a changing climate. To achieve these goals, cropping systems, tree species, management regimes, weather and soils may be effectively exploited if managers have the information and tools to wisely design their production systems. The first step is to develop farm-level analyses of potential windbreak scenarios that will tackle the social and environmental challenges of climate-change mitigation and adaptation based on the pillars of Climate Smart Agriculture.

## Research needs

According to Nair et al.,<sup>13</sup> agro forestry has come of age during the past three decades. The amount of scientific data has expanded, yet the understanding of C storage and dynamics in AFS is still minimal. Similarly, a comprehensive study of the C storage potential of AFS on the North American continent is lacking in the literature.<sup>180</sup> More research is necessary to more fully understand the performance of agro forestry as a GHG source or sink. The required inquiries include:

- i. Evaluating the emission and capture of nitrous oxides and methane,<sup>13</sup> developing standardized methodologies for estimating and reporting above- and belowground C stocks,<sup>181</sup>
- ii. Including C stored by agro forestry practices which are often left out in the current estimates;<sup>104</sup>
- iii. Analyzing soil C storage in layers deeper than 0.2m;<sup>87,106</sup>
- iv. Developing predictive models to simulate future climate and agro forestry systems<sup>44</sup>
- v. Assessing the dynamics of pests and diseases in agro forestry systems and developing more powerful methods to financially assess agro forestry practices;<sup>122</sup>
- vi. Developing accurate biomass equations to reliably estimate the C storage potential of agro forestry systems;<sup>182</sup>
- vii. Generating a wide range of agro forestry tree species for present and forthcoming climates;
- viii. Developing decision-support tools and models.<sup>83,183</sup>

From this list, one particular research need stands out - that accounting protocols and methodologies need to be developed for estimating C benefits from agro forestry plantings, especially at regional and national scales.<sup>184</sup> Agroforestry-specific equations are very limited,<sup>6,55,109,185</sup> because there is a lack of the regional and U.S.-wide data sets required for developing agro forestry-specific models that go into making C estimates.<sup>182</sup> Compared to forests, agro forestry plantings have a more open environment, resulting in trees with greater branch production and specific gravity.<sup>186</sup> These differences indicate that existing forest-derived equations may not accurately estimate tree biomass.<sup>186</sup>

In summary, current understanding of C capture and storage by agro forestry is limited and many uncertainties remain about the level of their impact on C budgets. Wide ranging data on agro forestry practices are not available to estimate accurate levels of direct and indirect C sequestration in the United States.<sup>15</sup> More comprehensive research, information decision-support tools and models need to be developed.<sup>183</sup> Although work remains regarding the research potential of agro forestry for North American agriculture, we need to be finding ways to use the science at-hand to assist those formulating land management decisions now.<sup>83,215-219</sup>

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## Conflicts of interest

Author declares that there is no conflicts of interest.



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