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Article

Site Productivity and Forest Carbon Stocks in the United States: Analysis and Implications for Forest Offset Project Planning

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Abstract: The documented role of United States forests in sequestering carbon, the relatively low cost of forest-based mitigation, and the many co-benefits of increasing forest carbon stocks all contribute to the ongoing trend in the establishment of forest-based carbon offset projects. We present a broad analysis of forest inventory data using site quality indicators to provide guidance to managers planning land acquisition for forest-based greenhouse gas mitigation projects. Specifically, we summarize two condition class indicators of site productivity within the FIA forest inventory database—PHYSCLCD and SITECLCD—as they relate to current aboveground live tree carbon stocks. Average carbon density is higher on more productive sites, but compared to the overall variability among sites, the differences are relatively small for all but the highest and lowest site classes. Some minor differences in eastern- *versus* western-forests were apparent in terms of how carbon on the least productive sites differed from most other forest land over time. Overall results suggest that xeric sites in most regions as well as sites that correspond to the lowest, non-productive classifications of forest land should preferentially not be used forestry-based greenhouse gas mitigation projects, but all other forest areas appear to be suitable.

Keywords: Forest Inventory and Analysis database; soil moisture regime; aboveground live biomass carbon; site productivity

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1. Introduction

In 2009 forests in the United States sequestered enough carbon to offset 13% of national greenhouse gas emissions [1]. This statistic highlights the importance of forests as a greenhouse gas mitigation tool, and the increasing emphasis on carbon sequestration as an ecosystem service provided by forests. Not only are land-based mitigation techniques often less costly to implement than other approaches [2], but maintaining and increasing forest carbon stocks can result in substantial co-benefits related to other management objectives such as water quality, wildlife habitat, and recreation. Forest carbon projects are implemented under a variety of programs, including UN-REDD and REDD+ (Reducing Emissions from Deforestation and Forest Degradation), the Clean Development Mechanism of the Kyoto Protocol, voluntary offset programs, and payments for ecosystem services partnerships.

Several analyses of potential strategies for increasing forest carbon sequestration are available (e.g., [3,4]); such strategies include afforestation of marginal lands, liquidation and regeneration of poorly stocked stands, and thinning treatments designed to increase mean annual increment. Another approach is the conservation or preservation of forested areas (through tools such as conservation easements or outright purchase) that are vulnerable to conversion to a nonforest land use. All of these options require planners and managers to weigh various criteria when deciding which parcels of land to select for a forest carbon mitigation project.

The influence of site productivity on forest biomass production is well known, and many management interventions are simply a means to increase the productive capacity of a site. The relationship between biomass production and site quality varies somewhat by species; related chronosequence studies in British Columbia found that the difference in aboveground biomass of paper birch between good sites and poor sites at age 60 was 90 t/ha, while for 65 year old aspen the difference was 76 t/ha [5,6]. A combination empirical/simulation study of maritime and radiata pine in Spain reported that site index had a large effect on carbon stocks, although increases in aboveground biomass on the best sites were substantially larger for maritime pine [7]. Keyes and Grier [8] measured net production in 40 year old Douglas fir stands and report values of 240 and 453 t/ha of aboveground biomass on low and high quality sites, respectively. In the cases cited above, site productivity was not explicitly defined. Comeau and Kimmins [9] compared 70 year old lodgepole pine stands on xeric and mesic sites and found that aboveground biomass on the mesic sites was 76–169 t/ha greater than on xeric sites. Finally, Kranabetter [10] examined a series of old-growth southern boreal stands in British Columbia, occupying a productivity gradient from xeric nutrient poor to subhygric very rich sites; aboveground biomass carbon stocks ranged from 75 tC/ha in the poor site to 360 tC/ha at the very rich site.

Although these site specific studies clearly illustrate the importance of site productivity on aboveground forest biomass accumulation, they provide little guidance for project developers, policymakers, or land managers deciding which parcels of land to target for forest-based greenhouse gas mitigation projects. In many regions, it is likely that forest land classified as higher productivity will carry with it a higher cost of acquisition. The USDA Forest Service Forest Inventory and Analysis Program (FIA) conducts ongoing surveys of forest land in the United States using a systematic standardized sampling protocol designed to achieve a specified error target at the state level [11]. The inventory data may be summarized by a variety of classification variables including ownership, stocking level, forest type, disturbance history, productivity class, state (or county), and many more. There are a number of carbon-related national and regional analyses that draw on the wide array of information in the FIA database (e.g., [12–14]); however, none utilize the site productivity classifications available in the database.

This study has two main objectives: (1) to summarize the carbon information in the FIA database by region and site quality indicator variables, and (2) to examine the resulting estimates for broad patterns that might inform decisions regarding site selection for forest-based greenhouse gas mitigation projects.

2. Experimental Section

All data used here were obtained from the Forest Inventory and Analysis Database (FIADB) Version 4.0 [15,16]. The FIA conducts surveys of United States forest lands including data obtained by field crew visits to a large array of permanent inventory plots [15]. These data are freely available for download from the Internet as the FIADB [16], and the specific data used here were downloaded on 17 August 2011. Data were processed consistent with methods of Bechtold and Patterson [11] and reduced to plot-level summaries. The analysis focused on the 48 conterminous states because these inventory data were the most complete and continuous, and data selected were the most recent survey available for each of these states.

Inventory plots comprise samples over an area that is most often approximately 0.6 ha; where selected measurements or attributes are not uniform across this area the plot is proportionally allocated to these different classifications, which are termed “condition classes” [11,15]. Aboveground live tree carbon density (metric tons of carbon per hectare, tC/ha), stand age, forest area, expansion factors (*i.e.*, hectares of forest represented by a condition class), plot location, and other site specific descriptive variables are summarized for each forested condition. Estimates of tree carbon are according to Jenkins *et al.* [17]. For this analysis, plot level data are resolved to separate summaries for each forested condition on each plot [15].

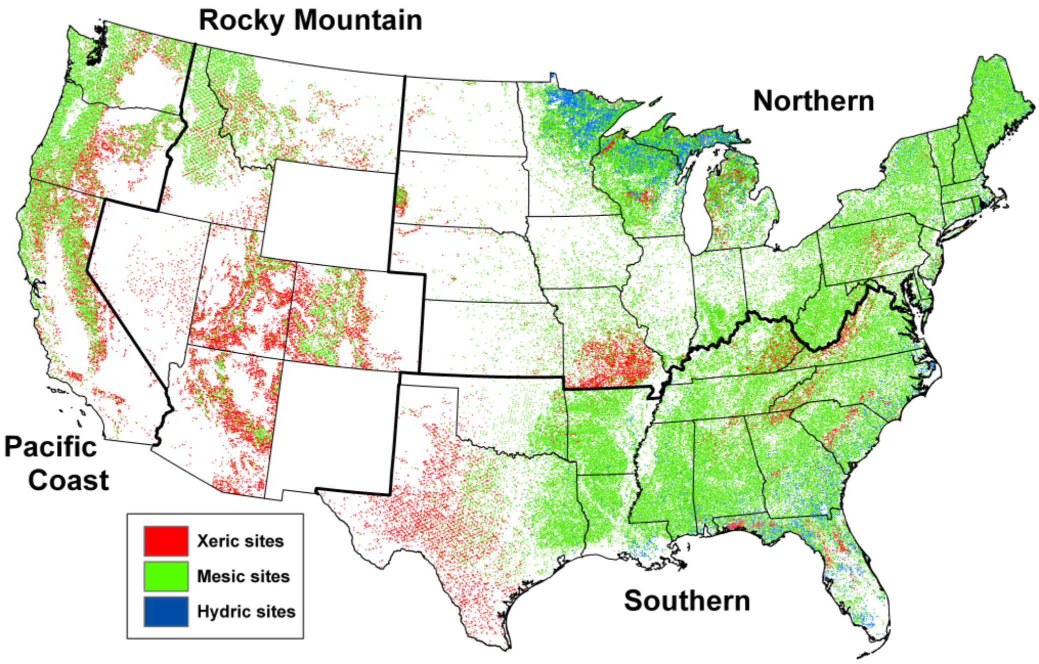
Two condition class variables [15] that we select for this overview—PHYSCLCD and SITECLCD—provide indicators of site stress or productivity that are independent of site preparation, management, or other forestry practices. Physiographic classes (PHYSCLCD) are described as xeric, mesic, or hydric and reflect effects of topographic position, landform, and soil texture on soil water status over the entire year. These classes should indicate likely long-term plant stress related to soil water levels. Site productivity class (SITECLCD) is a more direct quantification of site productivity within the FIADB in that it quantifies expected production of industrial wood as cubic feet of merchantable wood per acre per year (the FIADB is maintained in English units, as customary for forestry in the United States). The essential point of these two classifications is that they represent likely differences in forest productivity and still have some useful meaning even if characterized as potentially “more productive” *versus* “less productive”.

Carbon densities as summarized in the figures or tables are based on the tons carbon per hectare for each forest condition weighted according to its expansion factor. Because of our interest in informing forest carbon sequestration project planning, we exclude two forest type groups with consistently low tree carbon densities from the comparisons among carbon densities. Specifically, these groups are woodland hardwoods and nonstocked. Summaries according to age class represent the stand ages as provided in the current data. The most recent inventory data for all 48 states included values for SITECLCD, but PHYSCLCD was not available for New Mexico or Wyoming, so summary values based on PHYSCLCD omitted these two states from those particular result sets. The map is based on symbols located according to the approximate coordinates provided in the FIADB with each plot represented by a single color according to the physiographic class associated with that forest plot. Non-forest plots are not included, and plots with more than one physiographic class are represented by the majority condition.

3. Results and Discussion

Mesic is by far the most common soil water classification, or physiographic class, identified at FIA inventory plots (Figure 1). The symbols on the map represent the physiographic class associated with each forest inventory plot from the most recent survey data per state. Note that the symbols are not proportional to forest area, and are not included for New Mexico and Wyoming because the most recent data for those states do not include physiographic class. Xeric stands are much less frequent, but distributed throughout the four regions. Hydric sites are much more common in the East, and they are present in the West but infrequent. In the East they are more common in the Northern Lake States and along the coastal plains in the South.

Figure 1. Map of site physiographic class on FIA inventory plots. Blue = hydric, green = mesic, red = xeric. Symbols represent approximate location of forest plots.



Estimates of aboveground live tree carbon density (tC/ha) according to physiographic classification, age class, and region (see Figure 1) are summarized in Table 1 with associated forest areas in Table 2. Age classes were selected to reflect changes through stand growth and to be comparable among regional summaries. In some cases, the 90+ age classes include a large number of stands with ages well over 200 years; the first five age classes are more useful for analyzing possible outcomes of carbon sequestration projects. The number of inventory plots indicates the number of locations identified for each combination of physiographic condition class and age class. Because some inventory plots include proportional representation of more than one condition, a plot could be represented in more than one of the class combinations of Table 1. A specific example of this is a mesic site of a Pacific Coast forest split between a 90 year old western hemlock stand and a 45 year old Douglas-fir stand—the count for this plot appears twice in Table 1. As expected, mean carbon density is greater in older stands and mesic forests are most commonly associated with higher carbon densities. The generally lower carbon densities of the xeric and hydric classifications may be attributed to stress on those sites.

Table 1. Aboveground live tree (AGL) carbon density by physiographic class. SEM is standard error of the mean, and # plots is the number of FIA inventory plots.

	Hydric			**Mesic**			**Xeric**		
Age class (years)	**AGL (tC/ha)**	**SEM**	**# plots**	**AGL (tC/ha)**	**SEM**	**# plots**	**AGL (tC/ha)**	**SEM**	**# plots**
Northern Region									
15 to <30	13.3	1.68	350	29.0	0.37	3668	26.4	0.95	445
30 to <45	26.1	1.18	495	50.3	0.43	5625	43.4	1.00	593
45 to <60	35.8	0.96	865	66.6	0.39	8228	54.1	0.90	885
60 to <75	45.6	0.93	1031	79.4	0.39	8930	64.6	0.91	1032
75 to <90	50.8	1.10	828	88.6	0.48	6451	71.7	1.07	769
90 +	54.6	1.18	859	95.3	0.65	4281	77.6	1.49	528
Southern Region									
15 to <30	32.0	1.22	456	43.2	0.26	8799	18.2	0.76	601
30 to <45	52.4	1.49	533	54.1	0.39	6493	21.5	0.99	631
45 to <60	69.8	1.85	628	67.0	0.41	7578	34.0	1.15	754
60 to <75	84.9	2.37	466	80.3	0.52	6025	54.3	1.57	654
75 to <90	87.5	3.18	250	89.1	0.88	2730	62.5	1.94	490
90 +	102.6	5.16	146	96.7	1.55	1019	73.1	2.41	388
Rocky Mountain Region									
15 to <30	18.4	6.24	7	19.1	0.69	384	12.5	0.93	247
30 to <45	14.3	4.21	2	27.2	1.38	136	12.9	1.17	124
45 to <60	21.8	11.54	5	40.2	1.44	279	19.2	1.30	207
60 to <75	43.2	6.91	8	57.7	1.47	590	26.1	1.04	425
75 to <90	65.7	20.72	4	60.8	1.17	894	33.7	0.99	712
90 +	83.6	9.04	36	76.0	0.74	3532	35.1	0.43	4832
Pacific Coast Region									
15 to <30	65.0	9.56	15	52.3	1.18	1027	19.7	1.59	198
30 to <45	78.6	17.06	15	95.6	1.82	948	31.8	2.78	201
45 to <60	124.5	31.94	11	102.8	2.29	939	38.5	2.02	327
60 to <75	111.3	30.23	9	105.9	2.32	1000	44.5	1.82	542
75 to <90	64.5	15.17	12	107.2	2.31	1101	50.7	1.89	618
90 +	140.0	19.64	21	170.0	1.90	3472	73.1	1.75	1694

Note: Physiographic classes correspond to those shown in Figures 1 and 2.

Figure 2. Aboveground live tree carbon density (t/ha) by age class and physiographic class. Note that the 90+ year age class includes a range of age classes and may extend well past 200 years in some regions. (**a**) Northern Region; (**b**) Southern Region; (**c**) Rocky Mountain Region; (**d**) Pacific Coast Region.

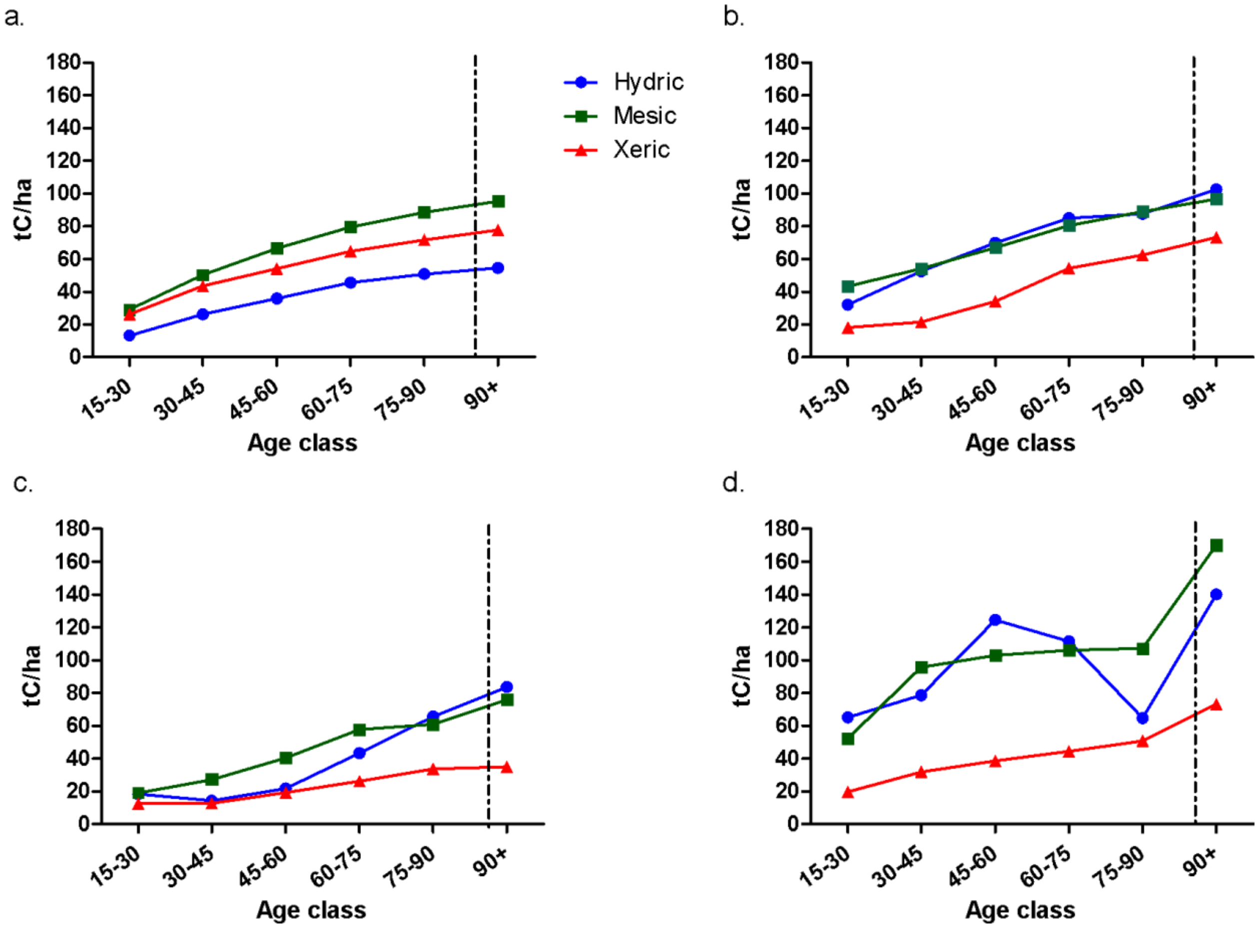


Table 2. Area of forest land included in the Table 1 summary by physiographic class and geographic region.

Region	Area of forest (Thousand hectares)		
	Hydric	Mesic	Xeric
Northern	4,927	57,820	6,880
Southern	4,325	63,088	10,418
Rocky Mountain	150	18,290	20,069
Pacific Coast	156	20,653	8,598

Note: Physiographic classes correspond to those shown in Figures 1 and 2.

The relative effects of stand age class and soil moisture classification are more readily illustrated by Figure 2. Xeric average densities were generally lowest throughout with the exception of the Northern region. The lower carbon densities of the hydric stands in the North may be related to forest type. The majority of hydric locations in the North are in Minnesota, Wisconsin, and Michigan. In fact, 73% of hydric forest lands in the North are on three forest type groups in those states; specifically, these are spruce-fir, elm-ash-cottonwood, and aspen-birch, which are generally lower carbon density groups throughout the North even on mesic sites. Average values for hydric stands in the South are very similar to mesic values. Note that the trends for hydric sites in the West (Figure 2) are based on very few plots (Table 1) over little forest area (Table 2).

Estimates of carbon density according to the other description of stand quality or potential for growth—site productivity—are provided in Table 3, which is also according to age class and region. Again, results can be generalized to higher carbon density with greater stand age class or higher productivity class. For purposes of evaluating likely sites for forest carbon sequestration, site productivity or SITECLCD may have limited meaning outside the context of the inventory plots. However, it is worth noting that the lowest productivity class in Table 3 (0–1.3 m^3/ha/yr) is considered nonproductive forest land. In general, the specific quantities associated with each class are not used here as a part of the analysis. They are however, useful as a general gradient of likely site productivity, and results are best evaluated in that context.

Table 3. Carbon density in aboveground live tree (AGL) biomass by productivity class. SEM is standard error of the mean, and # plots is the number of FIA inventory plots.

Age class	AGL (tC/ha)	SEM	# plots
Northern Region			
15.8+ m^3/ha/yr (225+ ft^3/ac/yr)			
15 to <30	52.6	12.57	4
30 to <45	67.1	8.34	8
45 to <60	82.9	9.00	7
60 to <75	–	–	–
75 to <90	–	–	–
90 +	54.7	–	1
11.6–15.7 m^3/ha/yr (165–224 ft^3/ac/yr)			
15 to <30	47.8	5.56	22
30 to <45	61.8	4.47	32
45 to <60	88.4	6.95	38
60 to <75	116.1	14.31	28
75 to <90	109.2	13.75	13
90 +	90.2	31.84	5
8.4–11.5 m^3/ha/yr (120–164 ft^3/ac/yr)			
15 to <30	40.5	1.85	222
30 to <45	64.1	1.94	428
45 to <60	80.0	2.04	435
60 to <75	85.8	2.45	297
75 to <90	103.6	3.33	149
90 +	98.2	5.30	72
5.6–8.3 m^3/ha/yr (85–119 ft^3/ac/yr)			
15 to <30	34.1	0.73	904
30 to <45	56.4	0.80	1680
45 to <60	72.0	0.76	2172
60 to <75	82.1	0.87	1773
75 to <90	93.7	1.37	906
90 +	100.0	1.97	479

Table 3. *Cont.*

Age class	AGL (tC/ha)	SEM	# plots
Northern Region			
3.5–5.5 m^3/ha/yr (50–84 ft^3/ac/yr)			
15 to <30	29.0	0.61	1381
30 to <45	48.7	0.63	2306
45 to <60	64.3	0.56	3550
60 to <75	77.9	0.58	3914
75 to <90	87.7	0.74	2588
90 +	97.0	1.03	1537
1.4–3.4 m^3/ha/yr (20–49 ft^3/ac/yr)			
15 to <30	23.8	0.52	1866
30 to <45	41.0	0.60	2215
45 to <60	57.2	0.55	3731
60 to <75	71.7	0.51	4911
75 to <90	80.7	0.58	4304
90 +	85.1	0.73	3427
0–1.3 m^3/ha/yr (0–19 ft^3/ac/yr)			
15 to <30	15.0	2.84	85
30 to <45	15.5	2.49	77
45 to <60	22.9	2.50	91
60 to <75	31.4	2.56	99
75 to <90	37.2	2.99	93
90 +	62.0	3.53	149
Southern Region			
15.8+ m^3/ha/yr (225+ ft^3/ac/yr)			
15 to <30	50.2	4.25	29
30 to <45	87.3	9.37	22
45 to <60	72.7	7.65	27
60 to <75	86.8	12.75	15
75 to <90	88.9	17.74	9
90 +	105.0	8.15	4
11.6–15.7 m^3/ha/yr (165–224 ft^3/ac/yr)			
15 to <30	51.7	0.70	984
30 to <45	67.4	1.98	260
45 to <60	81.3	2.46	233
60 to <75	100.0	3.85	158
75 to <90	101.4	6.06	63
90 +	102.4	16.37	16
8.4–11.5 m^3/ha/yr (120–164 ft^3/ac/yr)			
15 to <30	50.0	0.56	1893
30 to <45	66.7	1.10	976
45 to <60	78.3	1.15	962
60 to <75	88.8	1.52	639
75 to <90	98.9	2.80	239
90 +	108.0	5.33	72

Table 3. *Cont.*

Age class	AGL (tC/ha)	SEM	# plots
Southern Region			
5.6–8.3 m^3/ha/yr (85–119 ft^3/ac/yr)			
15 to <30	43.8	0.41	2914
30 to <45	60.1	0.65	2159
45 to <60	72.9	0.76	2358
60 to <75	87.1	1.07	1575
75 to <90	97.1	2.10	601
90 +	107.5	3.09	227
3.5–5.5 m^3/ha/yr (50–84 ft^3/ac/yr)			
15 to <30	39.7	0.44	3052
30 to <45	52.8	0.55	2802
45 to <60	69.3	0.58	3510
60 to <75	82.5	0.74	3048
75 to <90	94.1	1.11	1518
90 +	104.7	1.86	611
1.4–3.4 m^3/ha/yr (20–49 ft^3/ac/yr)			
15 to <30	27.8	0.79	743
30 to <45	42.7	0.91	914
45 to <60	59.6	0.88	1298
60 to <75	74.6	0.99	1387
75 to <90	82.6	1.36	808
90 +	96.2	2.20	481
0–1.3 m^3/ha/yr (0–19 ft^3/ac/yr)			
15 to <30	9.9	0.73	344
30 to <45	18.7	0.93	555
45 to <60	24.8	0.90	613
60 to <75	33.7	1.53	349
75 to <90	34.7	2.12	226
90 +	35.0	2.48	136
Rocky Mountain Region			
15.8+ m^3/ha/yr (225+ ft^3/ac/yr)			
15 to <30	–	–	–
30 to <45	–	–	–
45 to <60	–	–	–
60 to <75	–	–	–
75 to <90	–	–	–
90 +	–	–	–
11.6–15.7 m^3/ha/yr (165–224 ft^3/ac/yr)			
15 to <30	26.5	1.97	4
30 to <45	35.4	10.13	2
45 to <60	100.2	26.32	2
60 to <75	93.2	12.09	7
75 to <90	118.0	39.62	3
90 +	271.2	25.86	2

Table 3. *Cont.*

Age class	AGL (tC/ha)	SEM	# plots
Rocky Mountain Region			
8.4–11.5 m^3/ha/yr (120–164 ft^3/ac/yr)			
15 to <30	28.2	4.02	12
30 to <45	37.4	4.84	8
45 to <60	58.7	8.30	19
60 to <75	101.6	5.60	43
75 to <90	115.2	5.78	46
90 +	124.3	6.62	55
5.6–8.3 m^3/ha/yr (85–119 ft^3/ac/yr)			
15 to <30	19.3	2.29	23
30 to <45	40.4	4.97	11
45 to <60	55.9	3.13	51
60 to <75	72.1	3.95	92
75 to <90	86.4	3.69	119
90 +	109.3	2.97	335
3.5–5.5 m^3/ha/yr (50–84 ft^3/ac/yr)			
15 to <30	21.1	1.43	106
30 to <45	31.1	2.13	53
45 to <60	44.4	2.16	130
60 to <75	58.0	1.72	276
75 to <90	63.9	1.39	423
90 +	87.2	1.01	1725
1.4–3.4 m^3/ha/yr (20–49 ft^3/ac/yr)			
15 to <30	17.8	0.68	475
30 to <45	22.5	1.19	141
45 to <60	33.2	1.18	218
60 to <75	42.4	0.96	545
75 to <90	49.7	0.79	930
90 +	66.7	0.57	3889
0–1.3 m^3/ha/yr (0–19 ft^3/ac/yr)			
15 to <30	7.2	0.49	198
30 to <45	9.1	0.58	175
45 to <60	14.0	0.51	406
60 to <75	15.6	0.49	479
75 to <90	17.2	0.45	719
90 +	23.9	0.23	4742
Pacific Coast Region			
15.8+ m^3/ha/yr (225+ ft^3/ac/yr)			
15 to <30	79.7	4.97	51
30 to <45	122.8	5.64	58
45 to <60	157.1	8.85	52
60 to <75	175.7	14.38	24
75 to <90	213.5	25.04	19
90 +	236.6	18.56	37

Table 3. *Cont.*

Age class	AGL (tC/ha)	SEM	# plots
Pacific Coast Region			
11.6–15.7 m^3/ha/yr (165–224 ft^3/ac/yr)			
15 to <30	70.5	2.17	247
30 to <45	122.7	3.08	244
45 to <60	148.5	4.90	169
60 to <75	173.8	6.61	139
75 to <90	211.9	10.41	74
90 +	255.8	8.51	207
8.4–11.5 m^3/ha/yr (120–164 ft^3/ac/yr)			
15 to <30	50.7	1.85	416
30 to <45	103.6	2.94	355
45 to <60	113.6	4.47	296
60 to <75	129.5	4.86	255
75 to <90	146.3	5.06	237
90 +	229.0	4.05	880
5.6–8.3 m^3/ha/yr (85–119 ft^3/ac/yr)			
15 to <30	35.5	2.10	214
30 to <45	69.2	3.46	187
45 to <60	90.5	3.63	232
60 to <75	101.5	3.76	259
75 to <90	113.3	3.74	303
90 +	173.2	3.29	984
3.5–5.5 m^3/ha/yr (50–84 ft^3/ac/yr)			
15 to <30	24.5	2.06	157
30 to <45	47.3	3.26	166
45 to <60	55.3	2.53	262
60 to <75	65.8	2.22	374
75 to <90	75.4	2.28	444
90 +	125.2	2.39	1280
1.4–3.4 m^3/ha/yr (20–49 ft^3/ac/yr)			
15 to <30	22.2	2.50	104
30 to <45	26.4	3.33	78
45 to <60	38.8	2.86	128
60 to <75	48.4	2.06	264
75 to <90	57.8	2.34	378
90 +	88.9	2.07	1060
0–1.3 m^3/ha/yr (0–19 ft^3/ac/yr)			
15 to <30	16.9	2.75	50
30 to <45	14.2	2.56	78
45 to <60	23.3	2.48	137
60 to <75	27.6	2.24	235
75 to <90	30.7	2.20	270
90 +	48.4	2.19	729

Note: Productivity classes correspond to those shown in Figures 3 and 4.

The highest productivity classes are found in limited numbers in most regions, particularly the Northern and Rocky Mountain (Table 4). Similarly, xeric and hydric sites are considerably less common (Table 2, Figure 1) except for the Rocky Mountain region where xeric is most common. For these reasons, a clearer picture of relative effects of productivity is based on limiting summary values to mesic sites, which is provided in Figure 3. Mean values for the lowest productivity class are clearly lower and separate from the other class groups in all regions except Pacific Coast.

Table 4. Area of forest land included in the Table 3 summary by productivity class and geographic region.

Region	**Area of forest (Thousand hectares)**						
	15.8+ m^3/ha/yr (225+)	**11.6–15.7 m^3/ha/yr (165–224)**	**8.4–11.5 m^3/ha/yr (120–164)**	**5.6–8.3 m^3/ha/yr (85–119)**	**3.5–5.5 m^3/ha/yr (50–84)**	**1.4–3.4 m^3/ha/yr (20–49)**	**0–1.3 m^3/ha/yr (0–19)**
Northern	22	151	2,097	10,838	22,886	32,831	803
Southern	204	3,092	8,846	17,347	26,241	11,759	10,343
Rocky Mountain	–	79	688	2,172	8,128	17,240	19,941
Pacific Coast	617	2,626	5,745	5,265	6,468	4,899	3,787

Note: Productivity classes correspond to those shown in Figures 3 and 4. Productivity classes in parentheses are in units of cubic feet per acre per year.

The focus of the above results has been on regionally expected values based on site quality indicators and stand age. However, a carbon sequestration project is necessarily site specific, and stand to stand heterogeneity is such that a wide range of carbon densities contribute to these average values. Figure 4 illustrates the distribution of plot level values corresponding to the means for the Pacific Coast region from Figure 3. The vertical bars represent the range between the 25th and 75th percentiles of the plot level densities for each productivity class for two age classes, 15–30 years and 75–90 years. At age 75, the mid fifty percentile of plots are clearly different for the highest *versus* lowest productivity sites, but overall variability is high relative to differences among the means. A test for significance is not called for in this case because we are interested in illustrating the heterogeneous yet continuous trend among plots. Again, the particular values are not so important here. These ranges are typical for the trends illustrated in Figures 2 and 3 and indicate that while indicators of productivity are positively associated with levels of carbon density it is likely that more site-specific factors control actual carbon sequestration achieved per stand.

A common theme to the trends as illustrated in Figures 2 and 3 is that relative differences in mean carbon density among classifications were generally less in the East relative to the West. In addition, the differences among average values in the West tended to increase with stand age class. Differences in carbon associated with indicators of productivity were established early; this is apparent in that the relative rate of carbon increase over the first age class interval exceeded the mean rate for the next three intervals in 31 out of the 38 trends in the charts of Figures 2 and 3.

Figure 3. Aboveground live tree carbon density (t/ha) by age class and productivity class for plots classified as mesic. Note that the 90+ year age class includes a range of age classes and may extend well past 200 years in some regions. (**a**) Northern Region; (**b**) Southern Region; (**c**) Rocky Mountain Region; (**d**) Pacific Coast Region. Scales differ in panels c and d. Productivity classes correspond to those used in Table 3.

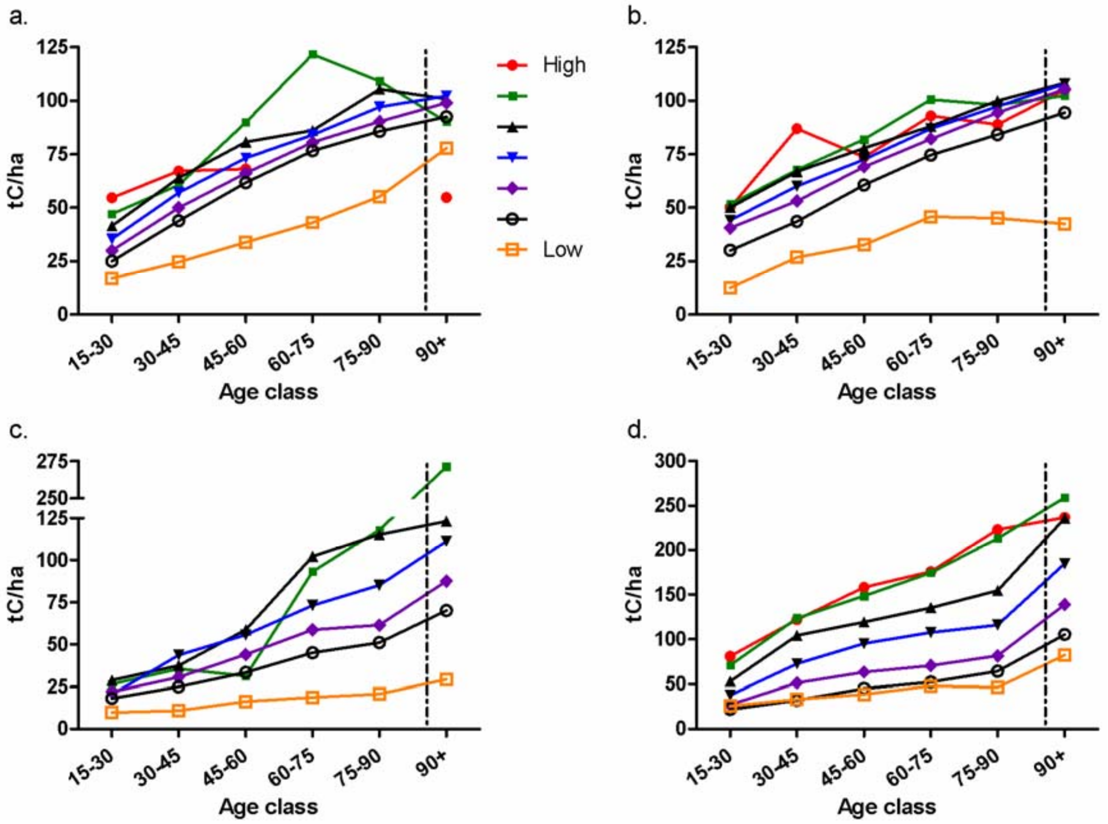
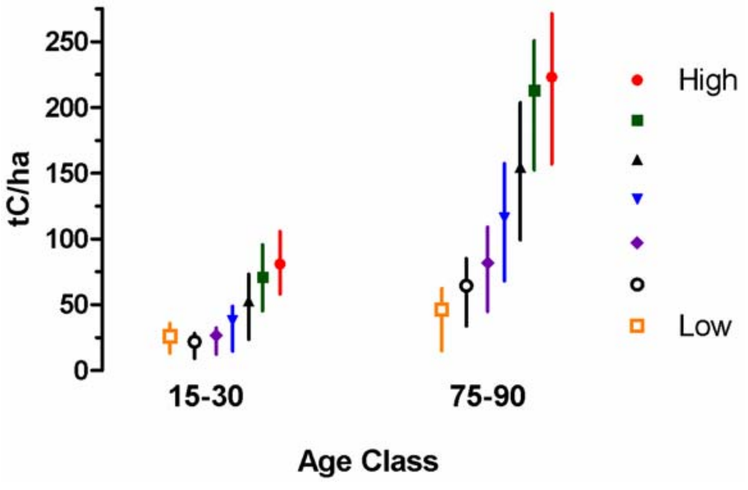
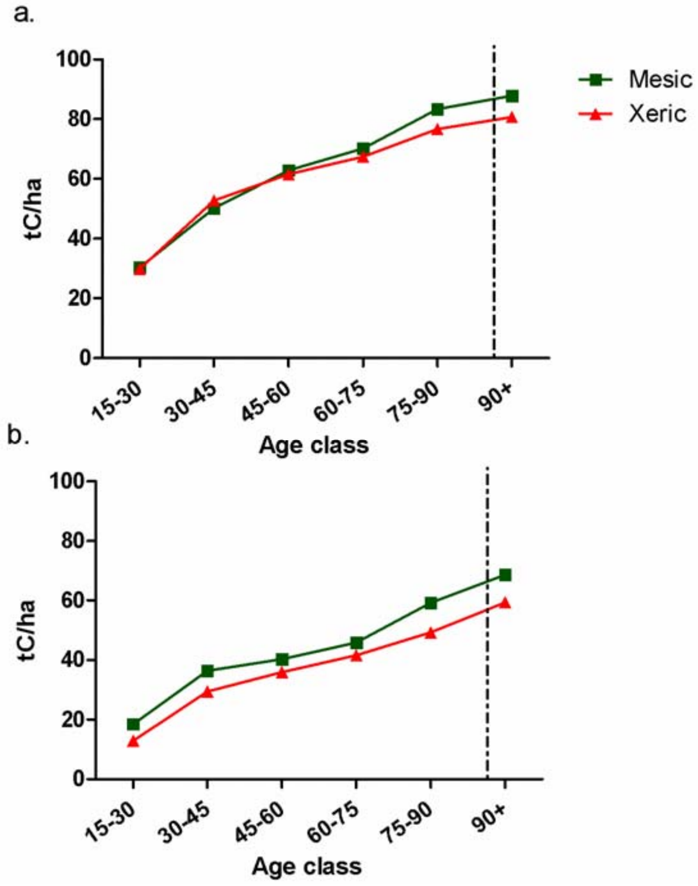


Figure 4. Distribution of carbon densities for mesic plots in the Pacific Coast Region by productivity class for younger and older age classes. Symbol indicates mean, top of error bar indicates 75th percentile, bottom of error bar indicates 25th percentile. Productivity classes correspond to those used in Table 3.



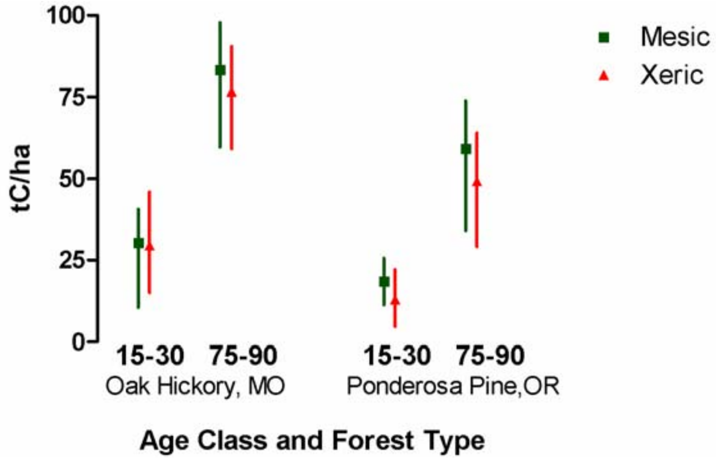
The distributions of plot level values together with the similarities in relative carbon accumulation apparent for the 30 to 75 year interval suggests that site quality is less of a predictor than factors affecting initial stand establishment. However, it is certainly likely that local exceptions exist where site conditions have a stronger influence on carbon density than is suggested by the large regional summaries. In general, the data agree with a sensitivity study in managed forests by Rötzer *et al.* [18], who found that thinning intensity generally had the strongest effect on net biomass productivity; site quality was also a factor, though its importance varied by species.

Figure 5. Aboveground live tree carbon density (t/ha) by age class and physiographic class for xeric and mesic plots in selected forest types and states. Note that the 90+ year age class includes a range of age classes and may extend well past 200 years in some regions. (**a**) Oak-hickory forest in Missouri; (**b**) Ponderosa pine forest in Oregon.



Analyses preliminary to the results presented here included segregating forests by type group, separation of softwood *versus* hardwood forest types and identifying sites with no evidence of disturbance or harvest. No additional insights were achieved by further subdividing the classifications presented above according to these approaches. However, to illustrate that a similar analysis produces similar results at, for example, a larger scale map (than Figure 1) and a more uniformly (or precisely) defined subset of forest land, we repeated the analysis for two forest types for individual states. The oak-hickory type group is widespread in the East, and the state of Missouri has the largest area of productive (e.g., above the lowest, nonproductive, site classification) oak-hickory forests. Similarly, ponderosa pine is a widespread softwood forest type group in the West, and Oregon has the largest area of ponderosa pine forest. Average carbon density according to age class and mesic *versus* xeric site conditions is shown in Figure 5 for these two types in the two states. The distribution of plot level carbon densities is shown in Figure 6. These results parallel the essential results from the more generalized regional summary values (Figures 2–4).

Figure 6. Distribution of carbon densities by physiographic class for xeric and mesic plots in selected forest types and states for younger and older age classes. Symbol indicates mean, top of error bar indicates 75th percentile, bottom of error bar indicates 25th percentile.



4. Conclusions

One of our objectives was to ascertain if the results of a large analysis of forest inventory data stratified by site class variables yielded general rules of thumb useful to managers planning forest-based greenhouse gas mitigation projects. Such guidance could inform decisions on which areas to target for project implementation. With the understanding that local site conditions may vary considerably from the regional trends presented here, a few common themes emerge. Average carbon density is higher on better sites, but compared to the overall variability among sites, these differences are relatively small for all but the highest and lowest site classes. There is a noticeable difference between the East and West in terms of site effects, with relative differences between site classes more pronounced in the West. With the exception of the North, xeric sites had lower carbon densities, while mesic and hydric sites were fairly comparable (though hydric sites are relatively rare in the West). Across all regions, differences in carbon density between age classes were generally greater for the younger age classes, as were the differences related to site quality. For the older age classes, the differences in relative increases in carbon density were less apparent.

Taken together, these results suggest that aside from avoiding the lowest quality sites, such as those classified as xeric in most regions (especially the Pacific Coast) and those in the lowest productivity class, most forest land may be suitable for forestry-based greenhouse gas mitigation projects. Provided that care is taken to ensure the establishment of a fully stocked stand, the extra cost associated with obtaining land identified as being more productive may not be warranted, especially in the East (noting that on a local level, there may be sites of exceptional productivity). Selection of project areas may also be contingent on the time horizon of the proposed project, because site-related relative differences in carbon accumulation over time also depend on stand age.

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Conflict of Interest

The authors declare no conflict of interest.

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