Supporting information

Using remote sensing to quantify the additional climate benefits of California forest carbon offset projects

Shane R. Coffield*, Cassandra D. Vo, Jonathan A. Wang, Grayson Badgley, Michael L. Goulden Danny Cullenward, William R. L. Anderegg, James T. Randerson

scoffiel@uci.edu

Here we present 6 additional figures and 4 additional tables supporting the results presented in the main text.

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Supporting Information

Fig S1. Comparison of remote sensing and reported carbon stocks and trends. eMapR and LEMMA estimates of carbon stocks are not significantly greater or less than reported carbon stocks across the portfolio of projects (top row), but have relatively high root mean square error against reported carbon stocks (30.9 and 29.2 ton C/ha, respectively). There is a slight bias to underestimate carbon stocks at high densities, especially with LEMMA. The largest discrepancies exist in estimations of the carbon accumulation rate over time (bottom half), with eMapR and LEMMA generally estimating lower magnitudes of change. Marker size indicates relative project area.
Fig S2. Demonstration of agreement across remote sensing datasets for an example project, CAR1066, which initiated in 2014 (dashed vertical line (b,d,f)). The harvest product by Wang et al. 2022 shows an expected pattern of patchwork clearcutting in this area over the available record of 1986-2021 (a). Harvest activity is fairly episodic, ranging from 0% to 7% of the area being cut each year (b). Both eMapR and LEMMA show substantial reductions in aboveground carbon in recently harvested patches (c, e), and loss of carbon in the timeseries aligns with large harvest events, despite the difference in absolute magnitude of carbon stocks between eMapR and LEMMA (d, f). Both eMapR and LEMMA capture steep declines followed by steady recovery for pixels that were harvested in 1989 (g) compared to non-harvested pixels over the record (h). The two carbon datasets agree in terms of rate of change of carbon over time, with approximately normal distributions of carbon sequestration rate across pixels, both for pixels recovering from harvest (i) or undisturbed (j). The means of the eMapR and LEMMA distributions are virtually equivalent as indicated by overlapping green and blue dashed lines.
Figure S3. Varying strategies of carbon crediting. Projects receive credits for additional carbon stocks from (1) initial stocking above baseline levels and (2) subsequent incremental increases over time, minus any estimated leakage or secondary effects. This presents a trade-off; projects with lower initial stocks are more likely to have high rates of accumulation such that they are still feasible for substantial crediting long-term. This is particularly the case for projects owned by large timber companies (defined in Table S3). Marker size indicates relative project areas.
Fig S4. Copy of Fig. 4, with added results for LEMMA carbon timeseries (c, d) and a third system of spatial controls based on covariate matching (purple lines). The LEMMA carbon timeseries shows a slower growth of carbon in the coastal region (c), but similar patterns of projects being relatively carbon-dense and adding carbon at similar rates as the control groups. The third control group - based on Mahalanobis distance matching to other pixels with most similar temperature, precipitation, and productivity in the same region - is shown in purple. This system of controls gave qualitatively similar results to the “surroundings” in black, apart from a decline in carbon in 1993 in the interior controls which is attributable to the 1992 Fountain Fire.
**Fig S5**: Before-and-after carbon accumulation and harvest rates by project. Asterisks* indicate statistical significance in the pre-to-post-project change, for an equal number of years considered before and after. For the 16 projects that started by 2014 (and excluding CAR1046 which terminated), 12 show a reduction in eMapR carbon accumulation rate after initiation (a), 10 of which are statistically significant (a). Four projects show an insignificant increase. LEMMA results are mostly similar, with predominantly decreases in carbon accumulation rate for projects (b); however one project, ACR200 does show a significant increase according to LEMMA. In terms of harvest, the four Sierra Pacific Industries projects (the four rightmost projects) show relatively high rates of harvest both before and after initiation. One project, CAR1092, has harvested significantly more since it became an offset project; none have harvested significantly less. The two systems of controls (gray and purple) differ in magnitudes of change but agree that the majority of areas show a decrease in carbon accumulation after projects begin.
Fig S6: Copy of Fig. 5, with an added panel for LEMMA results (b) and added bars for the third system of controls (purple). At this scale of grouping projects into two landowner categories, eMapR and LEMMA show the same direction of change for all cases – i.e., a decline in carbon accumulation rate.

The “matched controls” system performs similarly to the surrounding control areas, with the exception of the statistically insignificant increase in eMapR carbon accumulation and decrease in harvest rates for the timber company (interior) matched controls.
Table S1. Proportion of projects’ reported above ground standing live carbon (AGL) to the total standing live pool.

| Project ID | Average ratio of AGL to total carbon |
|------------|-------------------------------------|
| ACR173     | 0.806                               |
| ACR182     | 0.809                               |
| ACR378     | 0.806                               |
| CAR1013    | 0.805                               |
| CAR1046    | 0.789                               |
| CAR1102    | 0.807                               |
| CAR1103    | 0.809                               |
| CAR1104    | 0.808                               |
| CAR1141    | 0.815                               |
| CAR1174    | 0.807                               |
| CAR1330    | 0.804                               |
| CAR1368    | 0.807                               |
| CAR993     | 0.808                               |
| **Average**| 0.806                               |
| **Standard deviation** | 0.002 |
Table S2. Summary of carbon stocks and trends from three datasets. For each project, stocks and accumulation rates are calculated over the time period for which both inventory and eMapR or LEMMA data are available, at most 2012-2017. Therefore projects starting in 2017 or later are reported as n/a.

| Project ID | Area (ha) | Mean reported carbon stock (ton C/ha) | Mean eMapR carbon stock (ton C/ha) | Mean LEMMA carbon stock (ton C/ha) | Mean reported carbon accumulation (ton C/ha/y) | Mean eMapR carbon accumulation (ton C/ha/y) | Mean LEMMA carbon accumulation (ton C/ha/y) |
|------------|-----------|--------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| ACR173     | 2246      | 123.4                                | 115.3                             | 82.1                              | 2.3                                           | 1.3                                         | 0.7                                         |
| ACR182     | 968       | 139.8                                | 142.7                             | 111.9                             | 0.6                                           | 0.8                                         | 1.4                                         |
| ACR189     | 641       | 157.1                                | 128.6                             | 96.1                              | 3.3                                           | 0.6                                         | 0.9                                         |
| ACR200     | 714       | 135.1                                | 163.0                             | 104.3                             | 3.6                                           | 0.9                                         | 2.0                                         |
| ACR262     | 5328      | 133.1                                | 120.2                             | 103.9                             | 3.5                                           | 1.2                                         | 0.6                                         |
| ACR282     | 6064      | 113.8                                | 142.8                             | 123.6                             | 0.6                                           | 1.4                                         | -0.6                                        |
| ACR292     | 2202      | 127.8                                | 175.4                             | 110.6                             | 1.3                                           | -0.8                                        | -1.2                                        |
| ACR377     | 890       | 183.6                                | 135.6                             | 104.7                             | -2.0                                          | 0.4                                         | -0.1                                        |
| ACR378     | 782       | 207.7                                | 122.6                             | 97.8                              | -2.8                                          | -0.1                                        | 0.2                                         |
| CAR1013    | 7913      | 106.3                                | 143.4                             | 105.3                             | 1.9                                           | 1.6                                         | 1.6                                         |
| CAR1041    | 6863      | 110.1                                | 121.5                             | 114.1                             | 2.5                                           | 0.3                                         | -0.3                                        |
| CAR1046    | 4593      | 98.0                                 | 106.0                             | 106.6                             | -11.4                                         | -1.1                                        | 3.4                                         |
| CAR1066    | 5053      | 102.9                                | 87.6                              | 75.3                              | 3.2                                           | 0.9                                         | 0.7                                         |
| CAR1067    | 855       | 144.6                                | 132.9                             | 106.3                             | 3.6                                           | 1.4                                         | 1.7                                         |
| CAR1070    | 8411      | 133.7                                | 130.4                             | 106.8                             | 0.3                                           | 0.5                                         | -0.4                                        |
| CAR1092    | 5917      | 47.1                                 | 51.8                              | 41.6                              | 0.6                                           | 0.2                                         | 0.6                                         |
| CAR1095    | 6642      | 109.7                                | 98.1                              | 64.5                              | 4.5                                           | 1.6                                         | 1.0                                         |
| CAR1098    | 9624      | 122.2                                | 164.6                             | 108.4                             | 4.1                                           | 1.1                                         | 1.7                                         |
| CAR1099    | 5480      | 113.3                                | 167.2                             | 113.9                             | 4.2                                           | 1.6                                         | 1.4                                         |
| CAR1100    | 6439      | 124.7                                | 221.7                             | 138.6                             | 0.1                                           | 3.4                                         | 4.1                                         |
| CAR1102    | 1422      | 128.2                                | 139.5                             | 95.2                              | 1.1                                           | 0.5                                         | 0.3                                         |
| CAR1103    | 848       | 140.9                                | 119.9                             | 118.9                             | 0.9                                           | 1.2                                         | -0.3                                        |
| CAR1104    | 1416      | 126.1                                | 139.2                             | 120.0                             | 1.8                                           | 1.1                                         | 0.5                                         |
| CAR1114    | 7837      | 108.3                                | 94.7                              | 105.9                             | -0.2                                          | -1.1                                        | -1.1                                        |
| CAR1139    | 19418     | 146.3                                | 157.4                             | 109.4                             | 3.9                                           | 1.0                                         | 0.7                                         |
| CAR1140    | 7156      | 142.3                                | 146.7                             | 107.6                             | 6.6                                           | 1.2                                         | 2.0                                         |
| CAR1141    | 877       | 208.5                                | 226.8                             | 159.9                             | 2.3                                           | 1.0                                         | 1.2                                         |
|            | Width | Height | Area | Depth | Width | Height | Depth | Width | Height | Area | Depth | Width | Height | Depth |
|------------|-------|--------|------|-------|-------|--------|-------|-------|--------|------|-------|-------|--------|-------|
| CAR1174    | 1637  | 123.8  | 135.7| 93.1  | 1.6   | 0.9    | -0.1  | CAR1180 | 5005  | 152.4 | 140.4 | 115.1 | 2.7   | 0.3    | -0.2  |
| CAR1190    | 3491  | 141.5  | 168.2| 113.5 | 0.0   | 0.3    | 2.0   | CAR1191 | 8215  | 147.7 | 136.8 | 115.1 | 0.4   | 0.2    | 0.0   |
| CAR1313    | 749   | 269.6  | 191.8| 170.6 | n/a   | n/a    | n/a   | CAR1329 | 2547  | n/a   | n/a   | n/a   | n/a   | n/a    | n/a   |
| CAR1330    | 935   | n/a    | n/a  | n/a   | n/a   | n/a    | n/a   | CAR1339 | 13443 | n/a   | n/a   | n/a   | n/a   | n/a    | n/a   |
| CAR1368    | 3240  | n/a    | n/a  | n/a   | n/a   | n/a    | n/a   | CAR993  | 3100  | 136.8 | 136.7 | 103.9 | 4.4   | 0.7    | 0.5   |
| **Area-weighted average** |       | 125.7  | 137.4 | 105.2 | 1.97  | 0.83   | 0.82  |
| **Standard error** |       | 4.61   | 5.94  | 3.49  | 0.54  | 0.16   | 0.22  |
Table S3. Projects’ landowner information

| Project ID | Area (ha) | Offset Project Operator (OPO)                        | Category |
|------------|-----------|------------------------------------------------------|----------|
| ACR173     | 2246      | Round Valley Indian Tribes                           | other    |
| ACR182     | 968       | Forest Carbon Partners, LP                           | other    |
| ACR189     | 641       | Hanes Ranch Inc.                                     | other    |
| ACR200     | 714       | Edward Miller Trust                                  | other    |
| ACR262     | 5328      | Edward Miller Trust                                  | other    |
| ACR282     | 6064      | Western Rivers Forestry                              | other    |
| ACR292     | 2202      | Congaree River, LLC                                  | other    |
| ACR377     | 890       | California Timberlands 2, LLC                        | other    |
| ACR378     | 782       | California Timberlands 2, LLC                        | other    |
| CAR1013    | 7913      | Sustainable Conservation, Inc.                       | other    |
| CAR1041    | 6863      | Sierra Pacific Industries                            | timber   |
| CAR1046    | 4593      | Trinity Timberlands, LLC                             | other    |
| CAR1066    | 5053      | Sierra Pacific Industries                            | timber   |
| CAR1067    | 855       | Berry Summit, LLC                                    | other    |
| CAR1070    | 8411      | Yurok Tribe                                          | other    |
| CAR1092    | 5917      | Sierra Pacific Industries                            | timber   |
| CAR1095    | 6642      | Coastal Forestlands, Ltd.                            | other    |
| CAR1098    | 9624      | The Conservation Fund                                | other    |
| CAR1099    | 5480      | The Conservation Fund                                | other    |
| CAR1100    | 6439      | The Conservation Fund                                | other    |
| CAR1102    | 1422      | Montesol, LLC                                        | other    |
| CAR1103    | 848       | Ronald Glass                                         | other    |
| CAR1104    | 1416      | GM Gabrych Family LP                                 | other    |
| CAR1114    | 7837      | Sierra Pacific Industries                            | timber   |
| CAR1139    | 19418     | Usal Redwood Forest Company, LLC                     | other    |
| CAR1140    | 7156      | Coastal Ridges LLC                                   | other    |
| CAR1141    | 877       | Fred M. van Eck Forest Foundation                    | other    |
| CAR1174    | 1637      | Eddie Ranch Properties, LLC                          | other    |
| CAR1180    | 5005      | Mailliard Ranch                                      | other    |
| CAR1190    | 3491      | Mendocino Redwood Company, LLC                       | timber   |
| CAR1191    | 8215      | Mendocino Redwood Company, LLC                       | timber   |
| CAR1313    | 749       | Save the Redwoods League                             | other    |
| CAR1329    | 2547      | Hunter Ranch LLC                                     | other    |
| CAR   | 3-digit Code | Name                                      | Type |
|-------|--------------|-------------------------------------------|------|
| CAR1330 | 935          | Bohemian Club                             | other|
| CAR1339 | 13443        | Green Diamond Resource Company            | timber|
| CAR1368 | 3240         | California Timberlands 2, LLC             | other|
| CAR993  | 3100         | Yurok Tribe                               | other|
Table S4. Additionality criteria per project. We rate each project as passing (√) or failing (✗) our criteria as established in Table 1. While the specific details of any individual project are fairly uncertain and should not be scrutinized, this demonstrates a general pattern that the portfolio of projects does not show strong evidence of sequestering additional carbon. “-” indicates that the project was not evaluated on the given criteria, due to having less than three years since initiation or being outside the domain considered.

| Project ID | 1. Pre-project carbon | 2. Pre-project harvest | 3. Pre-project species | 4. Post-project carbon | 5. Post-project carbon |
|------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| ACR173     | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| ACR182     | ✓                      | ✓                      | ✓                      | ✓                      | ✓                      |
| ACR189     | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| ACR200     | ✓                      | ✓                      | ✓                      | ✓                      | ✓                      |
| ACR262     | ✓                      | ✓                      | ✓                      | -                      | -                      |
| ACR282     | ✓                      | ✓                      | ✓                      | -                      | -                      |
| ACR292     | ✓                      | ✓                      | ✓                      | -                      | -                      |
| ACR377     | ✓                      | ✓                      | -                      | -                      | -                      |
| ACR378     | ✓                      | ✓                      | -                      | -                      | -                      |
| CAR1013    | ✓                      | ✓                      | ✓                      | ✓                      | ✓                      |
| CAR1041    | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| CAR1046    | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| CAR1066    | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| CAR1067    | ✓                      | ✓                      | -                      | ✓                      | ✓                      |
| CAR1070 | ✗ | ✓ | - | - | - |
| CAR1092 | ✓ | ✗ | - | ✗ | ✗ |
| CAR1095 | ✗ | ✗ | - | ✗ | ✗ |
| CAR1098 | ✗ | ✓ | ✗ | - | - |
| CAR1099 | ✗ | ✓ | ✗ | - | - |
| CAR1100 | ✗ | ✗ | ✓ | - | - |
| CAR1102 | ✓ | ✓ | ✗ | - | - |
| CAR1103 | ✗ | ✓ | - | ✓ | ✓ |
| CAR1104 | ✗ | ✓ | - | ✗ | ✗ |
| CAR1114 | ✓ | ✓ | - | ✗ | ✗ |
| CAR1139 | ✗ | ✓ | ✗ | - | - |
| CAR1140 | ✗ | ✓ | ✗ | - | - |
| CAR1141 | ✗ | ✓ | ✓ | ✗ | ✗ |
| CAR1174 | ✗ | ✓ | - | - | - |
| CAR1180 | ✗ | ✗ | ✓ | - | - |
| CAR1190 | ✗ | ✓ | ✓ | - | - |
| CAR1191 | ✗ | ✓ | ✗ | - | - |
| CAR1313 | ✗ | ✓ | ✓ | - | - |
| CAR1329 | ✗ | ✓ | - | - | - |
| CAR1330 | ✗ | ✗ | ✗ | - | - |
| CAR1339 | ✗ | ✓ | ✗ | - | - |
| CAR1368 | ✗ | ✓ | - | - | - |
| CAR993 | ✗ | ✓ | - | ✗ | ✓ |