

- The second tier consists of determining whether or not the project is consistent with a GHG reduction plan that is part of a local general plan for example. The GHG reduction plan must, at a minimum, comply with AB 32 reduction goals; include emission estimates approved by CARB or SCAQMD, have been analyzed under CEQA, and have a certified Final CEQA document. Further, the GHG reduction plan must include a GHG inventory tracking mechanism; process to monitor progress in achieving GHG emission reduction targets, and a commitment to remedy the excess emissions if AB 32 goals are not met (enforcement). If the proposed project is consistent with the local GHG reduction plan, it is not significant for GHG emissions.

The concept of consistency with a GHG reduction plan, is similar to the concept of consistency in CEQA Guidelines §15125(d). If the proposed project does not comply with the local GHG reduction plan or no GHG reduction plan has been adopted, then move to the third tier.

- Under the third tier there are three options that can be used to demonstrate that a project would not have significant emissions. The first significance option is early compliance with AB 32 Scoping Plan measures. The second significance option, primarily for stationary source equipment, would be to install carbon best available retrofit control technology (BARCT) or best available control technology (BACT). Carbon BARCT/BACT would be established by the SCAQMD. The third significance option for industrial, commercial, and residential land use projects would be to implement a menu of prescribed mitigation measures. Mitigation measures would be developed for each land use sector by SCAQMD staff. Implementing one of these three options would result in a determination that GHG emission impacts from the proposed project are not significant. If the proposed project is unable to implement any one of these three options or cannot fully implement any option, then it would move to the fourth tier.
- Under the fourth tier, the lead agency would quantify GHG emissions from the project and implement offsite mitigation (GHG reduction projects) or purchase offsets. Under this tier, GHG emission impacts the lead agency would be required to mitigate or offset GHG emissions to zero. If GHG emissions can be offset to zero, GHG emissions from the project are concluded to be insignificant. If GHG impacts cannot be reduced to zero, the project is concluded to be significant for GHGs.

### **WORKING GROUP MEETING #3 (JUNE 19, 2008)**

Subsequent to Working Group meeting #2, SCAQMD staff received feedback on the initial staff proposal. Issues and concerns raised by the stakeholders on the initial staff proposal were addressed at the third Working Group meeting and are summarized in the following bullet points.

- The staff proposal does not explicitly state any quantitative or qualitative target objectives. If there are no explicit target objectives, how is it possible to determine whether or not a project is insignificant for GHG emissions?

- Concerns were raised regarding the lack of detail relative to the sector-specific mitigation measures and the potentially lengthy lag time between implementing the GHG significance threshold and developing the mitigation measures.
- For most projects, GHG emissions would not need to be calculated as long as the prescribed menu of sector-specific mitigation measures is implemented. Without quantifying GHG emissions and the control efficiencies of the mitigation measures, a project would be vulnerable to a “Fair Argument” that GHG emissions are still significant even after implementing prescribed mitigation measures.
- A CEQA document may be vulnerable in court if control efficiencies of mitigation measures are not identified.
- Is the staff proposal really a zero GHG significance?

Based on Working Group feedback, staff presented revised staff proposal #1, which consisted of a tiered decision tree approach. The components of revised staff proposal #1 are described in the following bullet points and shown graphically in Figure B-2. As shown in Figure B-2, some of the tier components of the revised staff proposal are similar to those in the initial staff proposal.

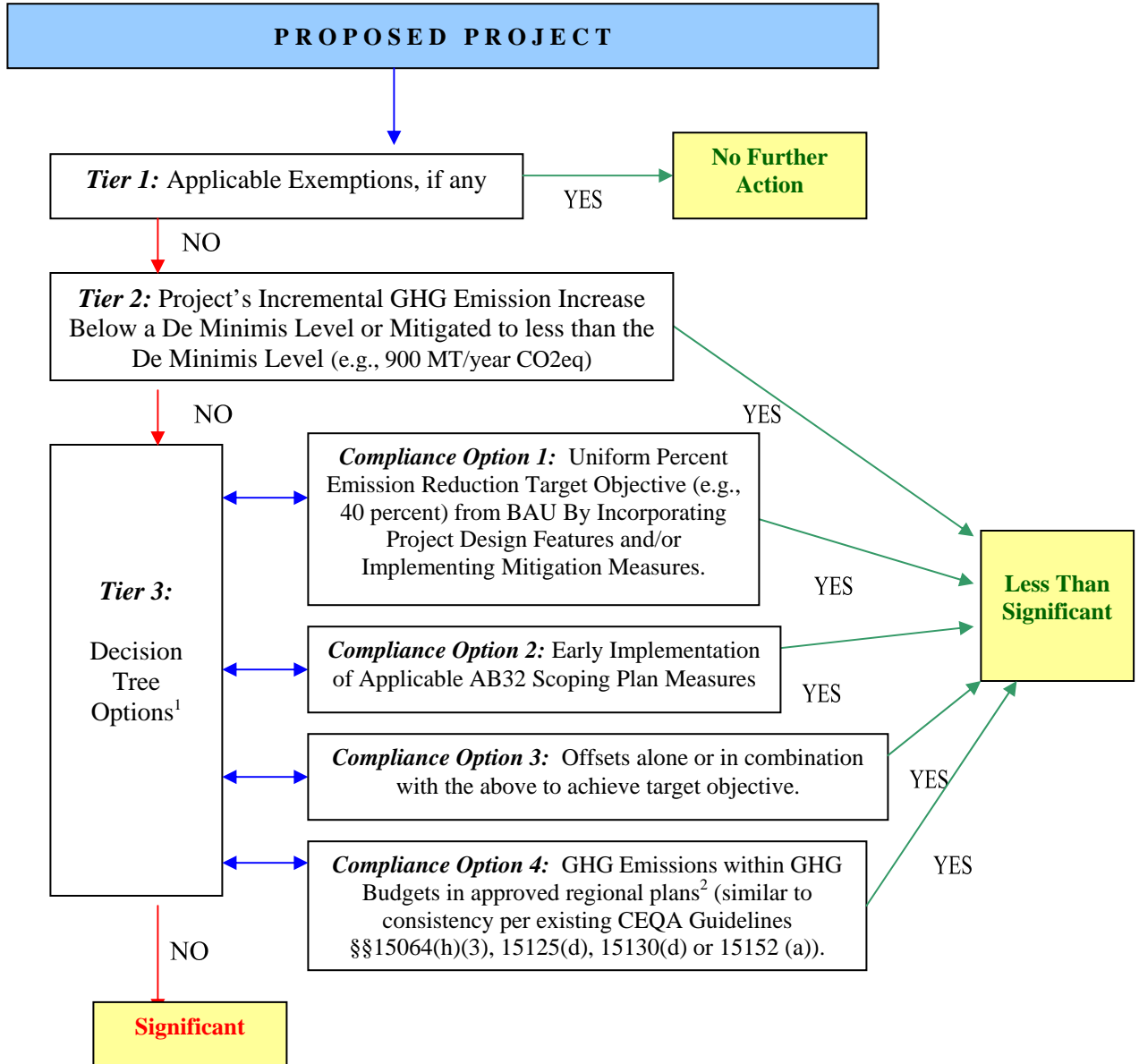
- **Tier 1** – no change from the initial proposal.
- **Tier 2** – is a new component of the revised staff proposal. Tier 2 attempts to identify small projects that would not likely contribute to significant cumulative GHG impacts. The de minimis or screening level of 900 metric tons per year is the level that is estimated by CAPCOA to capture 90 percent of the residential units or office space in pending application lists<sup>7</sup>. CAPCOA infers that projects that emit less than 900 metric ton per year would not likely be considered cumulatively considerable. Further, the 900 metric ton per year level would capture 90 percent

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<sup>7</sup> Although the CAPCOA White Paper implies that 900 metric tons per year equates to a 90 percent capture rate, there is no explicit information provided in the White Paper that demonstrates this correlation. Indeed, the CAPCOA authors state that 900 metric tons, which represents approximately 50 residential units, corresponds to widely divergent capture rate percentile rankings depending on the project location (see discussion on page 43 of the White Paper). Percentile rankings were based on a survey of four cities in California. A project of 900 metric tons per year representing a 90 percent capture rate appears to be a working assumption for which there appears to be no factual basis. Further, although not explicitly stated, it is assumed that the 900 metric tons were derived using the URBEMIS2007 model. It should be noted that that the URBEMIS2007 model only quantifies CO<sub>2</sub> emissions and direct emissions primarily from on-road mobile sources. It does not capture other GHG pollutants or indirect GHG emissions such as emissions from energy generation, water conveyance, etc. Therefore, it is likely that a 50-unit residential project would actually generate higher GHG emissions than 900 metric tons per year.

**Figure B-2**  
 Revised Staff Proposal #1 Tiered Decision Tree Approach – June 19, 2008

*Significance Determination of Cumulative Impacts from GHG Emissions:*



1. Substitution for equivalent reductions allowed.
2. Local General Plans or other local plans local plans that, at a minimum, comply with the overall target objective or the sector-based CARB Scoping Plan; have been analyzed under CEQA, and have a certified Final CEQA document; emission estimates approved by CARB or SCAQMD; include a GHG inventory; tracking mechanism; enforcement; and a commitment to remedy the excess emissions if commitments are not met.

of all pending projects, which means that 90 percent of all projects would have to implement GHG reduction measures.

If a project is less than 900 MT/year CO<sub>2</sub>eq or can mitigate to less than 900 MT/year CO<sub>2</sub>eq, it would be considered insignificant for GHGs. Projects larger than 900 MT/year CO<sub>2</sub>eq would move to tier 3.

- Tier 3 Decision Tree Options – consists of four decision tree options to demonstrate that a project is not significant for GHG emissions. The four compliance options are as follows.

**Compliance Option 1** – the lead agency would calculate GHG emissions for a project using a business-as-usual (BAU) methodology. Once GHG emissions are calculated, the project proponent would have to incorporate design features into the project and/or implement GHG mitigation measures to demonstrate a 40 percent reduction from BAU. A 40 percent reduction below BAU was selected for the following reason. To comply with the AB 32 requirement of reducing GHG emissions to 1990 levels, an approximately 30 percent reduction from current BAU is necessary.

Since CEQA is not applicable to all GHG emission sources, i.e., existing projects that are not undergoing expansion or modifications, staff chose a 40 percent reduction below BAU requirement, which goes beyond the target GHG reduction objective of AB 32, but is still a potentially feasible GHG reduction for a variety of different projects.

**Compliance Option 2** – this option is the same as the early compliance with AB 32 option in the third tier of the initial staff proposal.

**Compliance Option 3** – this option is similar to the fourth tier of the initial staff proposal where GHG emissions would be reduced through offsite GHG reduction projects and/or use of offsets. This compliance option, however, would require offsetting GHG emissions by the same target objective as compliance option 1, that is, 40 percent below BAU instead of reducing GHG emissions to less than the de minimis or screening level.

**Compliance Option 4** – this option is the same as the consistency with the greenhouse gas reduction plan component in the second tier of the initial staff proposal.

If the lead agency or project proponent cannot implement any of the compliance options in Tier 3, GHG emissions would be considered significant.

## **WORKING GROUP MEETING #4 (JULY 30, 2008)**

Subsequent to Working Group meeting #3, SCAQMD staff received feedback on the revised staff proposal #1. Issues and concerns raised by the stakeholders on the initial

staff proposal were addressed at the third Working Group meeting and are summarized in the following bullet points.

- Compliance with a GHG reduction plan should not be a compliance option in Tier 3, but should be its own tier, earlier in the tiering process.
- There is a large disconnect between screening level and remaining emissions under the Tier 4 compliance options. For example, large projects that can reduce GHG emissions by the target objective of 40 percent would do so, which means GHG emissions would not be significant, could have substantially higher emissions than projects with GHG emissions less than the screening level.
- Compliance with a target objective should not be through offsets alone. Because of the uncertainties regarding the validity of offsets, preferred mitigation should consist of actual GHG emission reductions.
- The Tier 3 compliance option 1, GHG emissions reductions from BAU, is not the proper metric for determining significance. How can a lead agency be sure that the projected BAU emissions for a project are not artificially inflated to make it easier to achieve the required target objective?
- The Tier 3 compliance option 1, reducing GHG emission reductions from BAU, could penalize projects in environmentally progressive areas where BAU may be much lower than in other areas, thus, making it more difficult to achieve the target objectives.

Based on Working Group feedback and internal discussions, staff presented revised staff proposal #2, which further refined the previous tiered decision tree approach. The components of revised staff proposal #2 are described in the following bullet points and shown graphically in Figure B-3. As shown in Figure B-3, some of the tier components of the revised staff proposal are similar to those in the initial staff proposal.

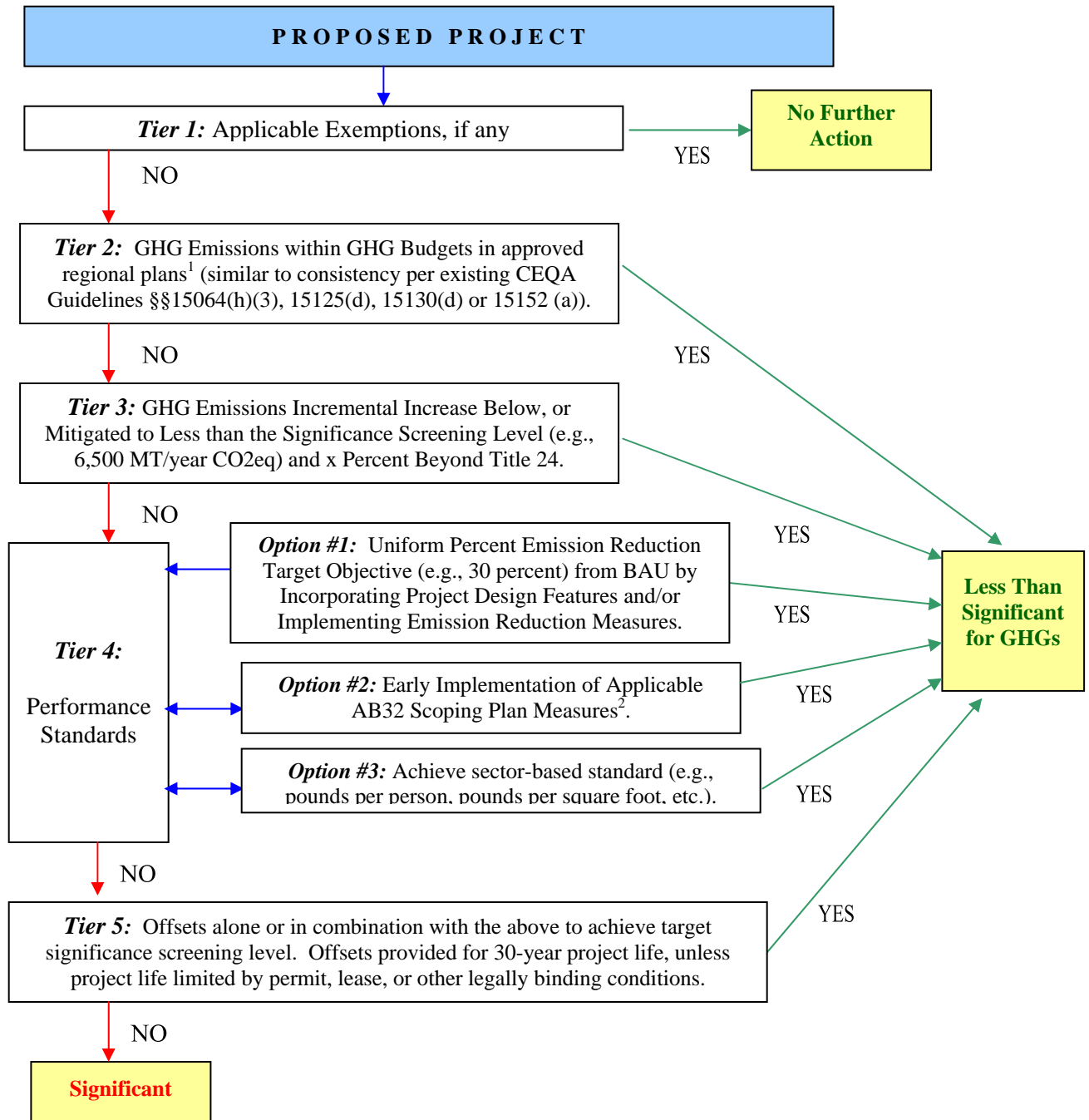
- **Tier 1** – no change from the initial proposal.
- **Tier 2** – compliance option 4 in Tier 3 has been moved back a stand-alone tier.
- **Tier 3** – the screening level that was previously Tier 2 has been moved to Tier 3. In response to feedback from the Working Group, the screening level has been increased to 6,500 MT/year CO<sub>2</sub>eq. The new screening level was derived using the SCAQMD's existing NO<sub>x</sub> operational threshold as a basis. The daily NO<sub>x</sub> operational significance threshold, 55 pounds per day was annualized, which results in 10 tons of NO<sub>x</sub> per year. Using the URBEMIS2007 model, staff initially modeled a mixed-use project that emits just under 10 tons per year to determine what the equivalent CO<sub>2</sub> emissions would be. Resulting CO<sub>2</sub> emissions from the mixed use project were approximately 6,500 MT/year CO<sub>2</sub>. To further corroborate the 6,500 MT/year CO<sub>2</sub> staff performed 19 modeling runs on a variety of projects including residential, commercial, industrial, and various combinations of land uses. In addition, since the analysis was an annual

analysis, a weighted trip rate was derived for each land use category to obtain a more accurate estimate of trip rates throughout the week. Although the results from the 19 modeling runs were approximately 16 percent higher than staff's original estimate of 6,500 MT/year CO<sub>2</sub>, 7,304 to 7,723 MT/year CO<sub>2</sub>, staff continued to recommend the 6,500 MT/year CO<sub>2</sub> provides a margin of safety when deriving CO<sub>2</sub> emissions based on the annualized NO<sub>x</sub> level of 10 tons per year and when evaluating different types of land use projects.

Projects with GHG emissions less than the screening level are considered to be small projects, that is, they would not likely be considered cumulatively considerable. However, because of the magnitude of increasing global temperatures from current and future GHG emissions, staff recommended that all projects must implement some measure or measures to contribute to reducing GHG emissions. Therefore, Tier 3 includes a requirement that all projects with GHG emissions less than the screening level must include efficiency components that reduce to a certain percentage beyond the requirements of Title 24 (Part 6, California Code of Regulations), California's energy efficiency standards for residential and nonresidential buildings.

- Tier 4 Performance Standards – Tier 3 from the revised staff proposal #1 has been moved to Tier 4 and renamed.

**Figure B-3**  
 Proposed Tiered Decision Tree Approach – July 30, 2008  
*Significance Determination of Cumulative Impacts from GHG Emissions:*



1. Local General Plans or other local plans local plans that, at a minimum, comply with the overall target objective or the sector-based CARB Scoping Plan; have been analyzed under CEQA, and have a certified Final CEQA document; emission estimates approved by CARB or SCAQMD; include a GHG inventory; tracking mechanism; enforcement; and a commitment to remedy the excess emissions if commitments are not met.
2. Substitution for equivalent reductions allowed.

**Compliance Option 1** – is essentially the same as the previously recommended, except that the target objective has been changed from reducing GHG emissions 40 percent below BAU to 30 percent below BAU to be more consistent with AB 32 target objectives.

**Compliance Option 2** – no change from the previous proposal.

**Compliance Option 3** – this is a new compliance option and consists of establishing sector-based performance standards. For example, it may be possible to use the 1990 inventory required under AB32 to establish an efficiency standard such as pounds per person, pounds per worker, pounds per square feet, pounds per item manufactured, etc. When calculating GHGs from a project, if they are less than the established efficiency standard the project would not be significant relative to GHG emissions, while projects exceeding the efficiency standard would be significant.

Projects that cannot comply with any of the compliance options in Tier 4 would then move on to Tier 5.

- **Tier 5** – consists generally of the Tier 3 compliance option 3 from the previous staff proposal. The only difference is that the project proponent would be required to provide offsets for the life of the project, which is defined as 30 years. If the project proponent is unable to obtain sufficient offsets, incorporate design features, or implement GHG reduction mitigation measures, then GHG emissions from the project would be considered significant.

## **WORKING GROUP MEETING #5 (AUGUST 27, 2008)**

Subsequent to Working Group meeting #3, SCAQMD staff received feedback on the revised staff proposal #2. Issues and concerns raised by the stakeholders on the initial staff proposal were addressed at the third Working Group meeting and are summarized in the following bullet points.

- A recommendation was made to modify the target objective of Tier 5 to be consistent with the target objective of Tier 4 compliance option 1, that is require emissions to be offset 30 percent from BAU rather than offset down to the screening level.
- A Working Group member asked for clarification on the early implementation of applicable AB 32 Scoping Plan measures in Tier 4-Option 2. In addition, a question was asked regarding whether or not this compliance option was applicable after the requirements of AB 32 have become effective.

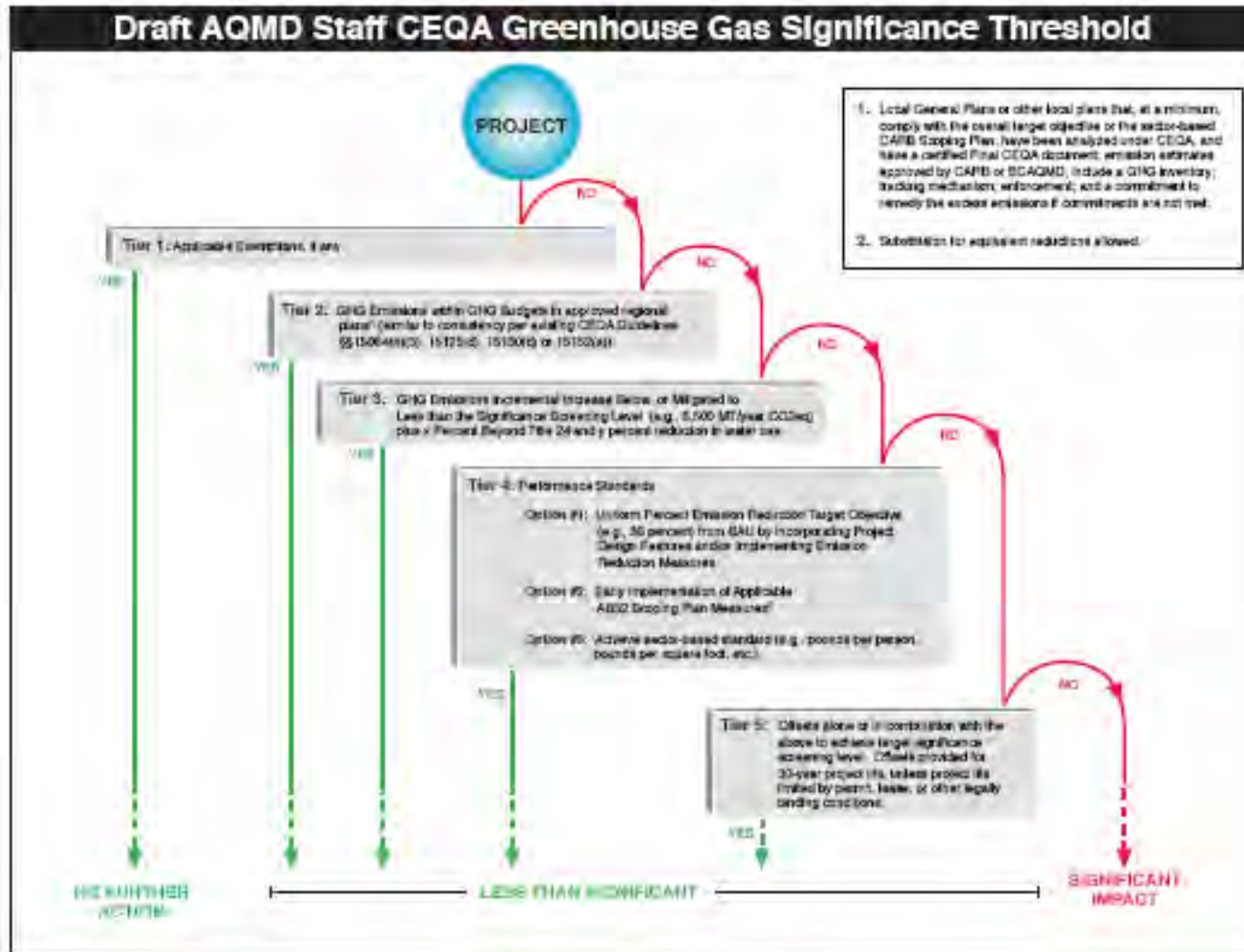
At Working Group meeting #5, staff presented revised staff proposal #3, which consisted primarily of minor refinements to the previous tiered decision tree approach



in revised staff proposal #2. The components of revised staff proposal #3 are shown graphically in Figure B-4.

Aside from changing the graphic layout of the staff proposal to make it easier to understand, revised staff proposal #3 has only one minor modification. A second energy efficiency requirement has been added to the screening level in Tier 3. In addition to requiring projects to go a certain percentage beyond Title 24, projects would also have to reduce by a specified percentage electricity demand from water use, primarily electricity used for water conveyance.

**Figure B-4**  
 Revised Staff Proposal #3 Tiered Decision Tree Approach – August 27, 2008





BAY AREA  
AIR QUALITY  
MANAGEMENT  
DISTRICT

**California Environmental Quality Act  
Guidelines Update**

**Proposed Thresholds of Significance**

**December 7, 2009**

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## Bay Area Air Quality Management District

# Proposed Air Quality CEQA Thresholds of Significance

## 1 INTRODUCTION

Bay Area Air Quality Management District (BAAQMD or Air District) staff analyzed various options for California Environmental Quality Act (CEQA) air quality thresholds of significance for use within BAAQMD's jurisdiction. The analysis and evaluation undertaken by Air District staff is documented in the *Revised Draft Options and Justification Report – California Environmental Quality Act Thresholds of Significance* (Draft Options Report) (BAAQMD October 2009).

Air District staff hosted public workshops in February, April, September and October 2009 at several locations around the Bay Area. In addition, Air District staff met with regional stakeholder groups to discuss and receive input on the threshold options being evaluated. Throughout the course of the public workshops and stakeholder meetings Air District staff received many comments on the various options under consideration. Based on comments received and additional staff analysis, the threshold options and staff-recommended thresholds were further refined. The culmination of this year-long effort was presented in the Proposed Thresholds of Significance Report published on November 2, 2009 as the Air District staff's proposed air quality thresholds of significance.

The Air District Board of Directors (Board) held public hearings on November 18 and December 2, 2009, to receive comments on staff's Proposed Thresholds of Significance (November 2009). After public testimony and Board deliberations, the Board requested staff to present additional options for risk and hazard thresholds for Board consideration. This Report includes risks and hazards threshold options, as requested by the Board, in addition to staff's previously recommended thresholds of significance. The proposed thresholds presented herein, upon adoption by the Air District Board of Directors, are intended to replace all of the Air District's currently recommended thresholds. The proposed air quality thresholds of significance, and Board-requested risk and hazard threshold options, are provided in Table 1 at the end of this introduction.

### 1.1 BAAQMD/CEQA REGULATORY AUTHORITY

The BAAQMD has direct and indirect regulatory authority over sources of air pollution in the San Francisco Bay Area Air Basin (SFBAAB). CEQA requires that public agencies consider the potential adverse environmental impacts of any project that a public agency proposes to carry out, fund or approve. CEQA requires that a lead agency prepare an Environmental Impact Report (EIR) whenever it can be fairly argued (the "fair argument" standard), based on substantial evidence,<sup>1</sup> that a project may have a significant effect<sup>2</sup> on

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<sup>1</sup> "Substantial evidence" includes facts, reasonable assumptions predicated upon facts, or expert opinions supported by facts, but does not include argument, speculation, unsubstantiated opinion or narrative, evidence that is clearly inaccurate or erroneous, or evidence of social or

the environment, even if there is substantial evidence to the contrary (CEQA Guidelines §15064). CEQA requires that the lead agency review not only a project's direct effects on the environment, but also the cumulative impacts of a project and other projects causing related impacts. When the incremental effect of a project is cumulatively considerable, the lead agency must discuss the cumulative impacts in an EIR. (CEQA Guidelines §15064).

The "fair argument" standard refers to whether a fair argument can be made that a project may have a significant effect on the environment (*No Oil, Inc. v. City of Los Angeles* (1974) 13 Cal.3d 68, 84). The fair argument standard is generally considered a low threshold requirement for preparation of an EIR. The legal standards reflect a preference for requiring preparation of an EIR and for "resolving doubts in favor of environmental review." *Meija v. City of Los Angeles* (2005) 130 Cal. App. 4th 322, 332. "The determination of whether a project may have a significant effect on the environment calls for careful judgment on the part of the public agency involved, based to the extent possible on scientific and factual data." (CEQA Guidelines §15064(b)).

In determining whether a project may have a significant effect on the environment, CEQA Guidelines Section 15064.7 provides that lead agencies may adopt and/or apply "thresholds of significance." A threshold of significance is "an identifiable quantitative, qualitative or performance level of a particular environmental effect, non-compliance with which means the effect will normally be determined to be significant by the agency and compliance with which means the effect normally will be determined to be less than significant" (CEQA Guidelines §15064.7).

While thresholds of significance give rise to a presumption of insignificance, thresholds are not conclusive, and do not excuse a public agency of the duty to consider evidence that a significant effect may occur under the fair argument standard. *Meija*, 130 Cal. App. 4th at 342. "A public agency cannot apply a threshold of significance or regulatory standard 'in a way that forecloses the consideration of any other substantial evidence showing there may be a significant effect.'" *Id.* This means that if a public agency is presented with factual information or other substantial evidence establishing a fair argument that a project may have a significant effect on the environment, the agency must prepare an EIR to study those impacts even if the project's impacts fall below the applicable threshold of significance.

Thresholds of significance must be supported by substantial evidence. This Report provides the substantial evidence in support of the thresholds of significance developed by the BAAQMD. If adopted by the BAAQMD Board of Directors, the Air District will recommend that lead agencies within the nine counties of the BAAQMD's jurisdiction

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economic impacts that do not contribute to, or are not caused by, physical impacts on the environment. Cal. Pub. Res. C. §21080(c); *see also* CEQA Guidelines §15384.

<sup>2</sup> A "significant effect" on the environment is defined as a "substantial, or potentially substantial, adverse change in the environment." Cal. Pub. Res. C. §21068; *see also* CEQA Guidelines §15382.

use the thresholds of significance in this Report when considering the air quality impacts of projects under their consideration.

## **1.2 JUSTIFICATION FOR UPDATING CEQA THRESHOLDS**

Any analysis of environmental impacts under CEQA includes an assessment of the nature and extent of each impact expected to result from the project to determine whether the impact will be treated as significant or less than significant. CEQA gives lead agencies discretion whether to classify a particular environmental impact as significant. Ultimately, formulation of a standard of significance requires the lead agency to make a policy judgment about where the line should be drawn distinguishing adverse impacts it considers significant from those that are not deemed significant. This judgment must, however, be based on scientific information and other factual data to the extent possible (CEQA Guidelines §15064(b)).

In the sense that advances in science provide new or refined factual data, combined with advances in technology and the gradual improvement or degradation of an environmental resource, the point where an environmental effect is considered significant is fluid over time. Other factors influencing this fluidity include new or revised regulations and standards, and emerging, new areas of concern.

In the ten years since BAAQMD last reviewed its recommended CEQA thresholds of significance for air quality, there have been tremendous changes that affect the quality and management of the air resources in the Bay Area. Traditional criteria air pollutant ambient air quality standards, at both the state and federal levels, have become increasingly more stringent. A new criteria air pollutant standard for fine particulate matter less than 2.5 microns in diameter (PM<sub>2.5</sub>) has been added to federal and state ambient air quality standards. We have found, through technical advances in impact assessment, that toxic air contaminants are not only worse than previously thought from a health perspective, but that certain communities experience high levels of toxic air contaminants, giving rise to new regulations and programs to reduce the significantly elevated levels of ambient toxic air contaminant concentrations in the Bay Area.

In response to the elevated levels of toxic air contaminants in some Bay Area communities, the Air District created the Community Air Risk Evaluation (CARE) Program. Phase 1 of the BAAQMD's CARE program compiled and analyzed a regional emissions inventory of toxic air contaminants (TACs), including emissions from stationary sources, area sources, and on-road and off-road mobile sources. Phase 2 of the CARE Program conducted regional computer modeling of selected TAC species, species which collectively posed the greatest risk to Bay Area residents. In both Phases 1 and 2, demographic data were combined with estimates of TAC emissions or concentrations to identify communities that are disproportionately impacted from high concentrations of TACs. Bay Area Public Health Officers, in discussions with Air District staff and in comments to the Air District's Advisory Council (February 11, 2009, Advisory Council Meeting on Air Quality and Public Health), have recommended that PM<sub>2.5</sub>, in addition to TACs, be considered in assessments of community-scale impacts of air pollution.



Bay Area AQMD Proposed Air Quality CEQA Thresholds of Significance  
December 7, 2009

Another significant issue that affects the quality of life for Bay Area residents is the growing concern with global climate change. In just the past few years, estimates of the global atmospheric temperature and greenhouse gas concentration limits needed to stabilize climate change have been adjusted downward and the impacts of greenhouse gas emissions considered more dire. Previous scientific assessments assumed that limiting global temperature rise to 2-3°C above pre-industrial levels would stabilize greenhouse gas concentrations in the range of 450-550 parts per million (ppm) of carbon dioxide-equivalent (CO<sub>2</sub>e). Now the science indicates that a temperature rise of 2°C would not prevent dangerous interference with the climate system. Recent scientific assessments suggest that global temperature rise should be kept below 2°C by stabilizing greenhouse gas concentrations below 350 ppm CO<sub>2</sub>e, a significant reduction from the current level of 385 ppm CO<sub>2</sub>e.

For the reasons stated above, and to further the goals of other District programs such as encouraging transit-oriented and infill development, BAAQMD has undertaken an effort to review all of its currently-recommended CEQA thresholds, revise them as appropriate, and develop new thresholds where appropriate. The overall goal of this effort is to develop CEQA significance criteria that ensure new development implements appropriate and feasible emission reduction measures to mitigate significant air quality impacts. The Air District's recommended CEQA significance thresholds have been vetted through a public review process and will be presented to the BAAQMD Board of Directors for adoption.

<b>Table 1 – Proposed Air Quality CEQA Thresholds of Significance</b>			
<b>Pollutant</b>	<b>Construction-Related</b>	<b>Operational-Related</b>	
<b>Project-Level</b>			
<b>Criteria Air Pollutants and Precursors (Regional)</b>	<b>Average Daily Emissions (lb/day)</b>	<b>Average Daily Emissions (lb/day)</b>	<b>Maximum Annual Emissions (tpy)</b>
ROG	54	54	10
NO <sub>x</sub>	54	54	10
PM <sub>10</sub> (exhaust)	82	82	15
PM <sub>2.5</sub> (exhaust)	54	54	10
PM <sub>10</sub> /PM <sub>2.5</sub> (fugitive dust)	Best Management Practices	None	
Local CO	None	9.0 ppm (8-hour average), 20.0 ppm (1-hour average)	
<b>GHGs Projects other than Stationary Sources</b>	None	Compliance with Qualified Climate Action Plan OR 1,100 MT of CO <sub>2</sub> e/yr OR 4.6 MT CO <sub>2</sub> e/SP/yr (residents + employees)	

Bay Area AQMD Proposed Air Quality CEQA Thresholds of Significance  
December 7, 2009

<b>Table 1 – Proposed Air Quality CEQA Thresholds of Significance</b>		
<b>Pollutant</b>	<b>Construction-Related</b>	<b>Operational-Related</b>
<b>GHGs</b> <b>Stationary Sources</b>	None	10,000 MT/yr
<b>Risks and Hazards</b> (Individual Project)  <b><u>Staff Proposal</u></b>	Same as Operational Thresholds*	<p><b><u>All Areas: Siting a New Source or Receptor</u></b></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;10.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2.5</sub> increase: &gt; 0.3 µg/m<sup>3</sup> annual average</p> <p><b><u>Zone of Influence:</u></b> 1,000-foot radius from fence line of source or receptor</p>
<b>Risks and Hazards</b> (Individual Project)  <b><u>Board Option 1</u></b>  <b>Tiered Thresholds</b>	Same as Operational Thresholds*	<p><b><u>Impacted Communities: Siting a New Source</u></b></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;5.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2.5</sub> increase: &gt; 0.2 µg/m<sup>3</sup> annual average</p> <p><b><u>Zone of Influence:</u></b> 1,000-foot radius from fence line of source or receptor</p>
	Same as Operational Thresholds*	<p><b><u>Impacted Communities: Siting a New Receptor</u></b> <b><u>All Other Areas: Siting a New Source or Receptor</u></b></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;10.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2.5</sub> increase: &gt; 0.3 µg/m<sup>3</sup> annual average</p> <p><b><u>Zone of Influence:</u></b> 1,000-foot radius from fence line of source or receptor</p>
<b>Risks and Hazards</b> (Individual Project)  <b><u>Board Option 2</u></b>  <b>Quantitative Thresholds</b>	Same as Operational Thresholds*	<p><b><u>All Areas: Siting a New Source or Receptor</u></b></p> <p>Increased cancer risk of &gt;10.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2.5</sub> increase: &gt; 0.3 µg/m<sup>3</sup> annual average</p> <p><b><u>Zone of Influence:</u></b> 1,000-foot radius from fence line of source or receptor</p>

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<b>Table 1 – Proposed Air Quality CEQA Thresholds of Significance</b>		
<b>Pollutant</b>	<b>Construction-Related</b>	<b>Operational-Related</b>
<b>Risks and Hazards</b> (Cumulative Thresholds)	Same as Operational Thresholds*	<p style="text-align: center;"><u>All Areas: Siting a New Source or Receptor</u></p> <p style="text-align: center;">Compliance with Qualified Risk Reduction Plan OR Cancer: &gt; 100 in a million (from all local sources) Non-cancer: &gt; 1.0 Hazard Index (from all local sources) (Chronic or Acute) PM<sub>2.5</sub>: &gt; 0.8 µg/m<sup>3</sup> annual average (from all local sources)</p> <p style="text-align: center;"><u>Zone of Influence:</u> 1,000-foot radius from fence line of source or receptor</p>
<b>Accidental Release of Acutely Hazardous Air Pollutants</b>	None	Storage or use of acutely hazardous materials locating near receptors or receptors locating near stored or used acutely hazardous materials considered significant
<b>Odors</b>	None	Screening Level Distances and Complaint History
<b>Plan-Level</b>		
<b>Criteria Air Pollutants and Precursors (Regional and Local)</b>	None	<ol style="list-style-type: none"> <li>1. Consistency with Current Air Quality Plan control measures</li> <li>2. Projected VMT or vehicle trip increase is less than or equal to projected population increase</li> </ol>
<b>GHGs</b>	None	Compliance with Qualified Climate Action Plan (or similar criteria included in a General Plan) OR 6.6 MT CO <sub>2</sub> e/ SP/yr (residents + employees)
<b>Risks and Hazards/Odors</b>	None	<ol style="list-style-type: none"> <li>1. Overlay zones around existing and planned sources of TACs (including adopted Risk Reduction Plan areas) and odors</li> <li>2. Overlay zones of at least 500 feet (or Air District-approved modeled distance) from all freeways and high volume roadways</li> </ol>
<b>Accidental Release of Acutely Hazardous Air Pollutants</b>	None	None
<p>Notes: CO = carbon monoxide; CO<sub>2</sub>e = carbon dioxide equivalent; GHGs = greenhouse gases; lb/day = pounds per day; MT = metric tons; NO<sub>x</sub> = oxides of nitrogen; PM<sub>2.5</sub>= fine particulate matter with an aerodynamic resistance diameter of 2.5 micrometers or less; PM<sub>10</sub> = respirable particulate matter with an aerodynamic resistance diameter of 10 micrometers or less; ppm = parts per million; ROG = reactive organic gases; SO<sub>2</sub> = sulfur dioxide; SP = service population; TACs = toxic air contaminants; TBP = toxic best practices; tons/day = tons per day; tpy = tons per year; yr= year.</p> <p>* Note: The Air District recommends that for construction projects that are less than one year duration, Lead Agencies should annualize impacts over the scope of actual days that peak impacts are to occur, rather than the full year.</p>		

## 2 GREENHOUSE GAS THRESHOLDS

BAAQMD does not currently have an adopted threshold of significance for GHG emissions. BAAQMD currently recommends that lead agencies quantify GHG emissions resulting from new development and apply all feasible mitigation measures to lessen the potentially adverse impacts. One of the primary objectives in updating the current CEQA Guidelines is to identify a GHG significance threshold, analytical methodologies, and mitigation measures to ensure new land use development meets its fair share of the emission reductions needed to address the cumulative environmental impact from GHG emissions. GHG emissions contribute, on a cumulative basis, to the significant adverse environmental impacts of global climate change. As reviewed herein, climate change impacts include an increase in extreme heat days, higher ambient concentrations of air pollutants, sea level rise, impacts to water supply and water quality, public health impacts, impacts to ecosystems, impacts to agriculture, and other environmental impacts. No single land use project could generate enough GHG emissions to noticeably change the global average temperature. The combination of GHG emissions from past, present, and future projects contribute substantially to the phenomenon of global climate change and its associated environmental impacts.

### 2.2 PROPOSED THRESHOLDS OF SIGNIFICANCE

Project Type	Proposed Thresholds
<b>Projects other than Stationary Sources</b>	Compliance with Qualified Climate Action Plan OR 1,100 MT of CO <sub>2</sub> e/yr OR 4.6 MT CO <sub>2</sub> e/SP/yr* (residents + employees)
<b>Stationary Sources</b>	10,000 MT of CO <sub>2</sub> e/yr
<b>Plans</b>	Compliance with Qualified Climate Action Plan (or similar criteria included in a General Plan) OR 6.6 MT CO <sub>2</sub> e/SP/yr (residents + employees)

\* Staff notes that the efficiency-based thresholds should be applied to individual projects with caution. As explained herein, lead agencies may determine that the efficiency-based GHG thresholds for individual land use projects may not be appropriate for very large projects. If there is a fair argument that the project's emissions on a mass level will have a cumulatively considerable impact on the region's GHG emissions, the insignificance presumption afforded to a project that meets an efficiency-based GHG threshold would be overcome.

### 2.3 JUSTIFICATION AND SUBSTANTIAL EVIDENCE SUPPORTING THRESHOLDS

BAAQMD's approach to developing a threshold of significance for GHG emissions is to identify the emissions level for which a project would not be expected to substantially conflict with existing California legislation adopted to reduce statewide GHG emissions.

If a project would generate GHG emissions above the threshold level, it would be considered to contribute substantially to a cumulative impact, and would be considered significant. If mitigation can be applied to lessen the emissions such that the project meets its share of emission reductions needed to address the cumulative impact, the project would normally be considered less than significant.

As explained in the District's *Revised Draft Options and Justifications Report* (BAAQMD 2009), there are several types of thresholds that may be supported by substantial evidence and be consistent with existing California legislation and policy to reduce statewide GHG emissions. In determining which thresholds to recommend, Staff studied numerous options, relying on reasonable, environmentally conservative assumptions on growth in the land use sector, predicted emissions reductions from statewide regulatory measures and resulting emissions inventories, and the efficacies of GHG mitigation measures. The thresholds recommended herein were chosen based on the substantial evidence that such thresholds represent quantitative and/or qualitative levels of GHG emissions, compliance with which means that the environmental impact of the GHG emissions will normally not be cumulatively considerable under CEQA. Compliance with such thresholds will be part of the solution to the cumulative GHG emissions problem, rather than hinder the state's ability to meet its goals of reduced statewide GHG emissions. Staff notes that it does not believe there is only one threshold for GHG emissions that can be supported by substantial evidence.

GHG CEQA significance thresholds recommended herein are intended to serve as interim levels during the implementation of the AB 32 Scoping Plan and SB 375, which will occur over time. Until AB 32 has been fully implemented in terms of adopted regulations, incentives, and programs and until SB 375 required plans have been fully adopted, or the California Air Resources Board (ARB) adopts a recommended threshold, the BAAQMD recommends that local agencies in the Bay Area apply the GHG thresholds recommended herein.

If left unchecked, GHG emissions from new land use development in California will result in a cumulatively considerable amount of GHG emissions and a substantial conflict with the State's ability to meet the goals within AB 32. Thus, BAAQMD proposes to adopt interim GHG thresholds for CEQA analysis, which can be used by lead agencies within the Bay Area. This would help lead agencies navigate this dynamic regulatory and technological environment where the field of analysis has remained wide open and inconsistent. BAAQMD's framework for developing a GHG threshold for land development projects that is based on policy and substantial evidence follows.

### **2.3.1 SCIENTIFIC AND REGULATORY JUSTIFICATION**

#### *Climate Science Overview*

Prominent GHGs contributing to the greenhouse effect are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons, chlorofluorocarbons, and sulfur hexafluoride. Human-caused emissions of these GHGs in excess of natural ambient concentrations are responsible for intensifying the greenhouse effect and have led to a

trend of unnatural warming of the earth's climate, known as global climate change or global warming. It is *extremely unlikely* that global climate change of the past 50 years can be explained without the contribution from human activities (IPCC 2007a).

According to Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), "Avoiding Dangerous Climate Change" means: "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.*" Dangerous climate change defined in the UNFCCC is based on several key indicators including the potential for severe degradation of coral reef systems, disintegration of the West Antarctic Ice Sheet, and shut down of the large-scale, salinity- and thermally-driven circulation of the oceans. (UNFCCC 2009). The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (IPCC 2007a). "Avoiding dangerous climate change" is generally understood to be achieved by stabilizing global average temperatures between 2 and 2.4°C above pre-industrial levels. In order to limit temperature increases to this level, ambient global CO<sub>2</sub> concentrations must stabilize between 350 and 400 ppm (IPCC 2007b).

#### ***Executive Order S-3-05***

Executive Order S-3-05, which was signed by Governor Schwarzenegger in 2005, proclaims that California is vulnerable to the impacts of climate change. It declares that increased temperatures could reduce the Sierra's snowpack, further exacerbate California's air quality problems, and potentially cause a rise in sea levels. To combat those concerns, the Executive Order established total GHG emission targets. Specifically, emissions are to be reduced to the 2000 level by 2010, the 1990 level by 2020, and to 80 percent below the 1990 level by 2050.

#### ***Assembly Bill 32, the California Global Warming Solutions Act of 2006***

In September 2006, Governor Arnold Schwarzenegger signed Assembly Bill 32, the California Global Warming Solutions Act of 2006, which set the 2020 greenhouse gas emissions reduction goal into law. AB 32 finds and declares that "Global warming poses a serious threat to the economic well-being, public health, natural resources, and the environment of California." AB 32 requires that statewide GHG emissions be reduced to 1990 levels by 2020, and establishes regulatory, reporting, voluntary, and market mechanisms to achieve quantifiable reductions in GHG emissions to meet the statewide goal.

In December of 2008, ARB adopted its *Climate Change Scoping Plan (Scoping Plan)*, which is the State's plan to achieve GHG reductions in California, as required by AB 32 (ARB 2008). The Scoping Plan contains strategies California will implement to achieve a reduction of 169 MMT CO<sub>2</sub>e emissions, or approximately 28 percent from the state's projected 2020 emission level of 596 MMT of CO<sub>2</sub>e under a business-as-usual scenario (this is a reduction of 42 MMT of CO<sub>2</sub>e, or almost 10 percent, from 2002-2004 average emissions), so that the state can return to 1990 emission levels, as required by AB 32.

While the Scoping Plan establishes the policy intent to control numerous GHG sources through regulatory, incentive, and market means, given the early phase of implementation and the level of control that local CEQA lead agencies have over numerous GHG sources, CEQA is an important and supporting tool in achieving GHG reductions overall in compliance with AB 32. In this spirit, BAAQMD is considering the adoption of thresholds of significance for GHG emissions for stationary source and land use development projects.

### ***Senate Bill 375***

Senate Bill (SB) 375, signed in September 2008, aligns regional transportation planning efforts, regional GHG reduction targets, and land use and housing allocation. SB 375 requires Metropolitan Planning Organizations (MPOs) to adopt a Sustainable Communities Strategy (SCS) or Alternative Planning Strategy (APS), which will prescribe land use allocation in that MPO's Regional Transportation Plan (RTP). ARB, in consultation with MPOs, will provide each affected region with reduction targets for GHGs emitted by passenger cars and light trucks in the region for the years 2020 and 2035. These reduction targets will be updated every eight years, but can be updated every four years if advancements in emission technologies affect the reduction strategies to achieve the targets. ARB is also charged with reviewing each MPO's SCS or APS for consistency with its assigned targets. If MPOs do not meet the GHG reduction targets, transportation projects would not be eligible for State funding programmed after January 1, 2012. New provisions of CEQA would incentivize qualified projects that are consistent with an approved SCS or APS, categorized as "transit priority projects."

While SB 375 is considered in the development of these thresholds, given that the Association of Bay Area Governments (ABAG) and the Metropolitan Transportation Commission (MTC) development of the SCS for the Bay Area is in its early stages and the ARB GHG reduction target for light duty and passenger vehicles in the Bay Area has not yet been proposed, it is not appropriate from a CEQA perspective to expect SB 375 to completely address the emission reductions needed from this transportation sector in meeting AB 32 goals. In the future, as SB 375 implementation progresses, BAAQMD may need to revisit GHG thresholds.

## **2.3.2 PROJECT-LEVEL GHG THRESHOLDS**

Staff recommends setting GHG significance thresholds based on AB 32 GHG emission reduction goals while taking into consideration emission reduction strategies outlined in ARB's Scoping Plan. Staff proposes two quantitative thresholds for land use projects: a bright line threshold based on a "gap" analysis and an efficiency threshold based on emission levels required to be met in order to achieve AB 32 goals.

Staff also proposes one qualitative threshold for land use projects: if a project complies with a Qualified Climate Action Plan (as defined in Section 2.3.4 below) that addresses the project it would be considered less than significant. As explained in detail in Section 2.3.4 below, compliance with a Qualified Climate Action Plan (or similar adopted policies, ordinances and programs), would provide the evidentiary basis for making

CEQA findings that development consistent with the plan would result in feasible, measurable, and verifiable GHG reductions consistent with broad state goals such that projects approved under qualified Climate Action Plans or equivalent demonstrations would achieve their fair share of GHG emission reductions.

### **2.3.2.1 LAND USE PROJECTS “GAP-BASED” THRESHOLD**

Staff took eight steps in developing this threshold approach, which are summarized here and detailed in the sections that follow. It should be noted that the “gap-based approach” used for threshold development is a conservative approach that focuses on a limited set of state mandates that appear to have the greatest potential to reduce land use development-related GHG emissions at the time of this writing. It is also important to note that over time, as the effectiveness of the State’s implementation of AB 32 (and SB 375) progresses, BAAQMD will need to reconsider the extent of GHG reductions needed over and above those from the implementation thereof for the discretionary approval of land use development projects. Although there is an inherent amount of uncertainty in the estimated capture rates (i.e., frequency at which project-generated emissions would exceed a threshold and would be subject to mitigation under CEQA) and the aggregate emission reductions used in the gap analysis, they are based on BAAQMD’s expertise, the best available data, and use conservative assumptions for the amount of emission reductions from legislation in derivation of the gap (e.g., only adopted legislation was relied upon). This approach is intended to attribute an appropriate share of GHG emission reductions necessary to reach AB 32 goals to new land use development projects in BAAQMD’s jurisdiction that are evaluated pursuant to CEQA.

Step 1 Estimate from ARB’s statewide GHG emissions inventory the growth in emissions between 1990 and 2020 attributable to “land use-driven” sectors of the emission inventory as defined by OPR’s guidance document (*CEQA and Climate Change*). Land use-driven emission sectors include Transportation (On-Road Passenger Vehicles; On-Road Heavy Duty), Electric Power (Electricity; Cogeneration), Commercial and Residential (Residential Fuel Use; Commercial Fuel Use) and Recycling and Waste (Domestic Waste Water Treatment).

Result: 1990 GHG emissions were 295.53 MMT CO<sub>2</sub>e/yr and projected 2020 business-as-usual GHG emissions would be 400.22 MMT CO<sub>2</sub>e/yr; thus a 26.2 percent reduction from statewide land use-driven GHG emissions would be necessary to meet the AB 32 goal of returning to 1990 emission levels by 2020. (See Table 2)

Step 2 Estimate the anticipated GHG emission reductions affecting the same land use-driven emissions inventory sectors associated with adopted statewide regulations identified in the AB 32 Scoping Plan.

Result: Estimated a 23.9 percent reduction can be expected in the land use-driven GHG emissions inventory from adopted Scoping Plan regulations, including AB 1493 (Pavley), LCFS, Heavy/Medium Duty Efficiency, Passenger Vehicle Efficiency, Energy-Efficiency



Measures, Renewable Portfolio Standard, and Solar Roofs. (See Table 3)

Step 3 Determine any short fall or “gap” between the 2020 statewide emission inventory estimates and the anticipated emission reductions from adopted Scoping Plan regulations. This “gap” represents additional GHG emission reductions needed statewide from the land use-driven emissions inventory sectors, which represents new land use development’s share of the emission reductions needed to meet statewide GHG emission reduction goals.

Result: With the 23.9 percent reductions from AB 32 Scoping Measures, there is a “gap” of 2.3 percent in necessary additional GHG emissions reductions to meet AB 32 goals of a 26.2 percent reduction from statewide land use-driven GHG emissions to return to 1990 levels in 2020. (See Table 2)

Step 4 Determine the percent reduction this “gap” represents in the “land use-driven” emissions inventory sectors from BAAQMD’s 2020 GHG emissions inventory. Identify the mass of emission reductions needed in the SFBAAB from land use-driven emissions inventory sectors.

Result: Estimated that a 2.3 percent reduction in BAAQMD’s projected 2020 emissions projections requires emissions reductions of 1.6 MMT CO<sub>2</sub>e/yr from the land use-driven sectors. (See Table 4)

Step 5 Assess BAAQMD’s historical CEQA database (2001-2008) to determine the frequency distribution trend of project sizes and types that have been subject to CEQA over the past several years.

Result: Determined historical patterns of residential, commercial and industrial development by ranges of average sizes of each development type. Results were used in Step 6 below to distribute anticipated Bay Area growth among different future project types and sizes.

Step 6 Forecast new land use development for the Bay Area using DOF/EDD population and employment projections and distribute the anticipated growth into appropriate land use types and sizes needed to accommodate the anticipated growth (based on the trend analysis in Step 5 above). Translate the land use development projections into land use categories consistent with those contained in the Urban Emissions Model (URBEMIS).

Result: Based on population and employment projections and the trend analysis from Step 5 above, forecasted approximately 4,000 new development projects, averaging about 400 projects per year through 2020 in the Bay Area.

Step 7 Estimate the amount of GHG emissions from each land use development project type and size using URBEMIS and post-model manual calculation methods (for emissions not included in URBEMIS). Determine the amount of GHG emissions that can reasonably and feasibly be reduced through currently available mitigation measures (“mitigation effectiveness”) for future land use development projects subject to CEQA (based on land use development projections and frequency distribution from Step 6 above).

Result: Based on the information available and on sample URBEMIS calculations, found that mitigation effectiveness of between 25 and 30 percent is feasible.

Step 8 Conduct a sensitivity analysis of the numeric GHG mass emissions threshold needed to achieve the desired emissions reduction (i.e., “gap”) determined in Step 4. This mass emission GHG threshold is that which would be needed to achieve the emission reductions necessary by 2020 to meet the Bay Area’s share of the statewide “gap” needed from the land use-driven emissions inventory sectors.

Result: The results of the sensitivity analysis conducted in Step 8 found that reductions between about 125,000 MT/yr (an aggregate of 1.3 MMT in 2020) and over 200,000 MT/yr (an aggregate of over 2.0 MMT in 2020) were achievable and feasible. A mass emissions threshold of 1,100 MT of CO<sub>2</sub>e/yr would result in approximately 59 percent of all projects being above the significance threshold (e.g., this is approximately the operational GHG emissions that would be associated with a 60 residential unit subdivision) and must implement feasible mitigation measures to meet CEQA requirements. With an estimated 26 percent mitigation effectiveness, the 1,100 MT threshold would achieve 1.6 MMT CO<sub>2</sub>e/yr in GHG emissions reductions.

### **2.3.2.2 DETAILED BASIS AND ANALYSIS**

#### ***Derivation of Greenhouse Gas Reduction Goal***

To meet the target emissions limit established in AB 32 (equivalent to levels in 1990), total GHG emissions would need to be reduced by approximately 28 percent from projected 2020 forecasts (ARB 2009a). The AB 32 Scoping Plan is ARB’s plan for meeting this mandate (ARB 2008). While the Scoping Plan does not specifically identify GHG emission reductions from the CEQA process for meeting AB 32 derived emission limits, the scoping plan acknowledges that “other strategies to mitigate climate change . . . should also be explored.” The Scoping Plan also acknowledges that “Some of the measures in the plan may deliver more emission reductions than we expect; others less . . . and new ideas and strategies will emerge.” In addition, climate change is considered a significant environmental issue and, therefore, warrants consideration under CEQA. SB 97 represents the State Legislature’s confirmation of this fact, and it directed the Governor’s Office of Planning and Research (OPR) to develop CEQA Guidelines for

evaluation of GHG emissions impacts and recommend mitigation strategies. In response, OPR released the *Technical Advisory: CEQA and Climate Change* (OPR 2008), and has released proposed CEQA guidelines (April 14, 2009) for consideration of GHG emissions. It is known that new land use development must also do its fair share toward achieving AB 32 goals (or, at a minimum, should not hinder the State's progress toward the mandated emission reductions).

***Foreseeable Scoping Plan Measures Emission Reductions and Remaining "Gap"***

Step 1 of the Gap Analysis entailed estimating from ARB's statewide GHG inventory the growth in emissions between 1990 and 2020 attributable to land use driven sectors of the emissions inventory. As stated above, to meet the requirements set forth in AB 32 (i.e., achieve California's 1990-equivalent GHG emissions levels by 2020) California would need to achieve an approximate 28 percent reduction in emissions across all sectors of the GHG emissions inventory compared with 2020 projections. However, to meet the AB 32 reduction goals in the emissions sectors that are related to land use development (e.g., on-road passenger and heavy-duty motor vehicles, commercial and residential area sources [i.e., natural gas], electricity generation/consumption, wastewater treatment, and water distribution/consumption), staff determined that California would need to achieve an approximate 26 percent reduction in GHG emissions from these land use-driven sectors (ARB 2009a) by 2020 to return to 1990 land use emission levels.

Next, in Step 2 of the Gap Analysis, Staff determined the GHG emission reductions within the land use-driven sectors that are anticipated to occur from implementation of the Scoping Plan measures statewide, which are summarized in Table 2 and described below. Since the GHG emission reductions anticipated with the Scoping Plan were not accounted for in ARB's or BAAQMD's 2020 GHG emissions inventory forecasts (i.e., business as usual), an adjustment was made to include (i.e., give credit for) GHG emission reductions associated with key Scoping Plans measures, such as the Renewable Portfolio Standard, improvements in energy efficiency through periodic updates to Title 24, AB 1493 (Pavley) (which recently received a federal waiver to allow it to be enacted in law), the Low Carbon Fuel Standard (LCFS), and other measures. With reductions from these State regulations (Scoping Plan measures) taken into consideration and accounting for an estimated 23.9 percent reduction in GHG emissions, in Step 3 of the Gap Analysis Staff determined that the Bay Area would still need to achieve an additional 2.3 percent reduction from projected 2020 GHG emissions to meet the 1990 GHG emissions goal from the land-use driven sectors. This necessary 2.3 percent reduction in projected GHG emissions from the land use sector is the "gap" the Bay Area needs to fill to do its share to meet the AB 32 goals. Refer to the following explanation and Tables 2 through 4 for data used in this analysis.

Because the transportation sector is the largest emissions sector of the state's GHG emissions inventory, it is aggressively targeted in early actions and other priority actions in the Scoping Plan including measures concerning gas mileage (Pavley), fuel carbon intensity (LCFS) and vehicle efficiency measures.

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<b>Table 2 – California 1990, 2002-2004, and 2020 Land Use Sector GHG<sup>1</sup></b> (MMT CO <sub>2</sub> e/yr)				
Sector	1990 Emissions	2002-2004 Average	2020 BAU Emissions Projections	% of 2020 Total
<b>Transportation</b>	<b>137.98</b>	<b>168.66</b>	<b>209.06</b>	<b>52%</b>
On-Road Passenger Vehicles	108.95	133.95	160.78	40%
On-Road Heavy Duty	29.03	34.69	48.28	12%
<b>Electric Power</b>	<b>110.63</b>	<b>110.04</b>	<b>140.24</b>	<b>35%</b>
Electricity	95.39	88.97	107.40	27%
Cogeneration <sup>2</sup>	15.24	21.07	32.84	8%
<b>Commercial and Residential</b>	<b>44.09</b>	<b>40.96</b>	<b>46.79</b>	<b>12%</b>
Residential Fuel Use	29.66	28.52	32.10	8%
Commercial Fuel Use	14.43	12.45	14.63	4%
<b>Recycling and Waste<sup>1</sup></b>	<b>2.83</b>	<b>3.39</b>	<b>4.19</b>	<b>1%</b>
Domestic Wastewater Treatment	2.83	3.39	4.19	1%
<b>TOTAL GROSS EMISSIONS</b>	<b>295.53</b>	<b>323.05</b>	<b>400.22</b>	
% Reduction Goal from Statewide land use driven sectors (from 2020 levels to reach 1990 levels in these emission inventory sectors)			26.2%	
% Reduction from AB32 Scoping Plan measures applied to land use sectors (see Table 3)			-23.9%	
% Reduction needed statewide beyond Scoping Plan measures (Gap)			2.3%	
Notes: MMT CO <sub>2</sub> e /yr = million metric tons of carbon dioxide equivalent emissions per year.				
<sup>1</sup> Landfills not included. See text.				
<sup>2</sup> Cogeneration included due to many different applications for electricity, in some cases provides substantial power for grid use, and because electricity use served by cogeneration is often amenable to efficiency requirements of local land use authorities.				
Sources: Data compiled by EDAW and ICF Jones & Stokes from ARB data.				

Pavley Regulations. The AB 32 Scoping Plan assigns an approximate 20 percent reduction in emissions from passenger vehicles associated with the implementation of AB 1493. The AB 32 Scoping Plan also notes that “AB 32 specifically states that if the Pavley regulations do not remain in effect, ARB shall implement alternative regulations to control mobile sources to achieve equivalent or greater reductions of greenhouse gas emissions (HSC §38590).” Thus, it is reasonable to assume full implementation of AB 1493 standards, or equivalent programs that would be implemented by ARB. While the Obama administration has proposed national CAFE standards that may be equivalent to or even surpass AB 1493, the timing for implementation of the proposed federal standards is uncertain such that development of thresholds based on currently unadopted federal standards would be premature. BAAQMD may need to revisit this methodology as the federal standards come on line, particularly if such standards are more aggressive than that forecast under state law.

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<b>Table 3 – 2020 Land Use Sector GHG Emission Reductions from State Regulations and AB 32 Measures</b>				
<b>Affected Emissions Source</b>	<b>California Legislation</b>	<b>% Reduction from 2020 GHG inventory</b>	<b>End Use Sector (% of Bay Area LU Inventory)</b>	<b>Scaled % Emissions Reduction (credit)</b>
Mobile	AB 1493 (Pavley)	19.7%	On road passenger/light truck transportation (45%)	8.9%
	LCFS	7.2%	On road passenger/light truck transportation (45%)	3.2%
	LCFS	7.2%	On road Heavy/Medium Duty Transportation (5%)	0.4%
	Heavy/Medium Duty Efficiency	2.9%	On road Heavy/Medium Duty Transportation (5%)	0.2%
	Passenger Vehicle Efficiency	2.8%	On road passenger/light truck transportation (45%)	1.3%
Area	Energy-Efficiency Measures	9.5%	Natural gas (Residential, 10%)	1.0%
			Natural gas (Non-residential, 13%)	1.2%
Indirect	Renewable Portfolio Standard	21.0%	Electricity (excluding cogen) (17%)	3.5%
	Energy-Efficiency Measures	15.7%	Electricity (26%)	4.0%
	Solar Roofs	1.5%	Electricity (excluding cogen) (17%)	0.2%
Total credits given to land use-driven emission inventory sectors from Scoping Plan measures				<b>23.9%</b>
Notes: AB = Assembly Bill; LCFS = Low Carbon Fuel Standard; SB = Senate Bill; RPS = Renewable Portfolio Standard Please refer to Appendix D for detailed calculations. Sources: Data compiled by ICF Jones & Stokes.				

LCFS. According to the adopted LCFS rule (CARB, April 2009), the LCFS is expected to result in approximately 10 percent reduction in the carbon intensity of transportation fuels. However, a portion of the emission reductions required from the LCFS would be achieved over the life cycle of transportation fuel production rather than from mobile-source emission factors. Based on CARB’s estimate of nearly 16 MMT reductions in on-road emissions from implementation of the LCFS and comparison to the statewide on-road emissions sector, the LCFS is assumed to result in a 7.2 percent reduction compared to 2020 BAU conditions (CARB 2009e).

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<b>Table 4 – SFBAAB 1990, 2007, and 2020 Land Use Sector GHG Emissions Inventories and Projections (MMT CO<sub>2</sub>e/yr)</b>				
Sector	1990 Emissions	2007 Emissions	2020 Emissions Projections	% of 2020 Total <sup>2</sup>
<b>Transportation</b>	<b>26.1</b>	<b>30.8</b>	<b>35.7</b>	<b>50%</b>
On-Road Passenger Vehicles	23.0	27.5	32.0	
On-Road Heavy Duty	3.1	3.3	3.7	
<b>Electric Power</b>	<b>25.1</b>	<b>15.2</b>	<b>18.2</b>	<b>26%</b>
Electricity	16.5	9.9	11.8	
Cogeneration	8.6	5.3	6.4	
<b>Commercial and Residential</b>	<b>8.9</b>	<b>15.0</b>	<b>16.8</b>	<b>24%</b>
Residential Fuel Use	5.8	7.0	7.5	
Commercial Fuel Use	3.1	8.0	9.3	
<b>Recycling and Waste<sup>1</sup></b>	<b>0.2</b>	<b>0.4</b>	<b>0.4</b>	<b>1%</b>
Domestic Waste Water Treatment	0.2	0.4	0.4	
<b>TOTAL GROSS EMISSIONS</b>	<b>60.3</b>	<b>61.4</b>	<b>71.1</b>	
SFBAAB's "Fair Share" % Reduction (from 2020 levels to reach 1990 levels) with AB-32 Reductions (from Table 3)			2.3%	
SFBAAB's Equivalent Mass Emissions Land Use Reduction Target at 2020 (MMT CO <sub>2</sub> e/yr)			1.6	
Notes: MMT CO <sub>2</sub> e /yr = million metric tons of carbon dioxide equivalent emissions per year; SFBAAB = San Francisco Bay Area Air Basin.				
<sup>1</sup> Landfills not included.				
<sup>2</sup> Percentages do not sum exactly to 100% in table due to rounding.				
Please refer to Appendix D for detailed calculations.				
Sources: Data compiled by EDAW 2009, ICF Jones & Stokes 2009, BAAQMD 2008.				

**Renewable Portfolio Standard, Energy Efficiency and Solar Roofs.** Energy efficiency and renewable energy measures from the Scoping Plan were also included in the gap analysis. The Renewable Portfolio Standard (rules) will require the renewable energy portion of the retail electricity portfolio to be 33 percent in 2020. For PG&E, the dominant electricity provider in the Basin, approximately 12 percent of their current portfolio qualifies under the RPS rules and thus the gain by 2020 would be approximately 21 percent. The Scoping Plan also estimates that energy efficiency gains with periodic improvement in building and appliance energy standards and incentives will reach 10 to 15 percent for natural gas and electricity respectively. The final state measure included in this gap analysis is the solar roof initiative, which is estimated to result in reduction of the overall electricity inventory of 1.5 percent.

Landfill emissions are excluded from this analysis. While land use development does generate waste related to both construction and operations, the California Integrated Waste Management Board (CIWMB) has mandatory diversion requirements that will, in all probability, increase over time to promote waste reductions, reuse, and recycle. The Bay Area has relatively high levels of waste diversion and extensive recycling efforts. Further, ARB has established and proposes to increase methane capture requirements for all major landfills. Thus, at this time, landfill emissions associated with land use

development waste generation is not included in the land use sector inventory used to develop this threshold approach.

Industrial stationary sources thresholds were developed separately from the land use threshold development using a market capture approach as described below. However, mobile source and area source emissions, as well as indirect electricity emissions that derive from industrial use are included in the land use inventory above as these particular activities fall within the influence of local land use authorities in terms of the affect on trip generation and energy efficiency.

AB 32 mandates reduction to 1990-equivalent GHG levels by 2020, with foreseeable emission reductions from State regulations and key Scoping Plan measures taken into account, were applied to the land use-driven emission sectors within the SFBAAB (i.e., those that are included in the quantification of emissions from a land use project pursuant to a CEQA analysis [on-road passenger vehicles, commercial and residential natural gas, commercial and residential electricity consumption, and domestic waste water treatment], as directed by OPR in the Technical Advisory: *Climate Change and CEQA* [OPR 2008]). This translates to a 2.3 percent gap in necessary GHG emission reductions by 2020 from these sectors.

#### **2.3.2.3 LAND USE PROJECTS BRIGHT LINE THRESHOLD**

In Steps 4 and 5 of the gap analysis, Staff determined that applying a 2.3 percent reduction to these land use emissions sectors in the SFBAAB's GHG emissions inventory would result in an equivalent fair share of 1.6 million metric tons per year (MMT/yr) reductions in GHG emissions from new land use development. As additional regulations and legislation aimed at reducing GHG emissions from land use-related sectors become available in the future, the 1.6 MMT GHG emissions reduction goal may be revisited and recalculated by BAAQMD.

In order to derive the 1.6 MMT "gap," a projected development inventory for the next ten years in the SFBAAB was calculated. (See Table 4 and *Revised Draft Options and Justifications Report* (BAAQMD 2009).) CO<sub>2e</sub> emissions were modeled for projected development in the SFBAAB and compiled to estimate the associated GHG emissions inventory. The GHG (i.e., CO<sub>2e</sub>) CEQA threshold level was adjusted for projected land use development that would occur within BAAQMD's jurisdiction over the period from 2010 through 2020.

Projects with emissions greater than the threshold would be required to mitigate to the threshold level or reduce project emissions by a percentage (mitigation effectiveness) deemed feasible by the Lead Agency under CEQA compared to a base year condition. The base year condition is defined by an equivalent size and character of project with annual emissions using the defaults in URBEMIS and the California Climate Action Registry's General Reporting Protocol for 2008. By this method, land use project mitigation subject to CEQA would help close the "gap" remaining after application of the key regulations and measures noted above supporting overall AB 32 goals.

This threshold takes into account Steps 1-8 of the gap analysis described above to arrive at a numerical mass emissions threshold. Various mass emissions significance threshold levels (i.e., bright lines) could be chosen based on the mitigation effectiveness and performance anticipated to be achieved per project to meet the aggregate emission reductions of 1.6 MMT needed in the SFBAAB by 2020. (See Table 5 and *Revised Draft Options and Justifications Report* (BAAQMD 2009).) Staff recommends a 1,100 MT CO<sub>2</sub>e per year threshold. Choosing a 1,100 MT mass emissions significance threshold level (equivalent to approximately 60 single-family units), would result in about 59 percent of all projects being above the significance threshold and having to implement feasible mitigation measures to meet their CEQA obligations. These projects account for approximately 92 percent of all GHG emissions anticipated to occur between now and 2020 from new land use development in the SFBAAB.

Project applicants and lead agencies could use readily available computer models to estimate a project's GHG emissions, based on project specific attributes, to determine if they are above or below the bright line numeric threshold. With this threshold, projects that are above the threshold level, after consideration of emission-reducing characteristics of the project as proposed, would have to reduce their emissions to below the threshold to be considered less than significant.

Establishing a "bright line" to determine the significance of a project's GHG emissions impact provides a level of certainty to lead agencies in determining if a project needs to reduce its GHG emissions through mitigation measures and when an EIR is required.



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December 7, 2009

<b>Table 5 – Operational GHG Threshold Sensitivity Analysis</b>								
<b>Option</b>	<b>Mitigation Effectiveness Assumptions</b>		<b>Mass Emission Threshold Level (MT CO<sub>2</sub>e/yr)</b>	<b>% of Projects Captured (&gt;threshold)</b>	<b>% of Emissions Captured (&gt; threshold)</b>	<b>Emissions Reduction per year (MT/yr)</b>	<b>Aggregate Emissions Reduction (MMT) at 2020</b>	<b>Threshold Project Size Equivalent (single family dwelling units)</b>
	<b>Performance Standards Applied to All Projects with Emissions &lt; Threshold Level</b>	<b>Mitigation Effectiveness Applied to Emissions &gt; Threshold Level</b>						
1A	N/A	30%	975	60%	93%	201,664	2.0	53
1A	N/A	25%	110	96%	100%	200,108	2.0	66
1A	N/A	30%	1,225	21%	67%	159,276	1.6	67
1A	N/A	26%	1,100	59%	92%	159,877	1.6	60
1A	N/A	30%	2,000	14%	61%	143,418	1.4	109
1A	N/A	25%	1,200	58%	92%	136,907	1.4	66
1A	N/A	30%	3,000	10%	56%	127,427	1.3	164
1A	N/A	25%	1,500	20%	67%	127,303	1.3	82
1B	26%	N/A	N/A	100%	100%	208,594	2.1	N/A <sup>1</sup>
1C	5%	30%	1,900	15%	62%	160,073	1.6	104
1C	10%	25%	1,250	21%	67%	159,555	1.6	68
1C	5%	30%	3,000	10%	56%	145,261	1.5	164
1C	10%	25%	2,000	4%	61%	151,410	1.5	109
1C	10%	30%	10,000	2%	33%	125,271	1.3	547

Notes: MMT = million metric tons per year; MT CO<sub>2</sub>e/yr = metric tons of carbon dioxide equivalent emissions per year; MT/yr = metric tons per year; N/A = not applicable.  
<sup>1</sup> Any project subject to CEQA would trigger this threshold.  
Please refer to Appendix E for detailed calculations.  
Source: Data modeled by ICF Jones & Stokes.

**2.3.2.4 LAND USE PROJECTS EFFICIENCY-BASED THRESHOLD**

GHG efficiency metrics can also be utilized as thresholds to assess the GHG efficiency of a project on a per capita basis (residential only projects) or on a “service population” basis (the sum of the number of jobs and the number of residents provided by a project) such that the project will allow for consistency with the goals of AB 32 (i.e., 1990 GHG emissions levels by 2020). GHG efficiency thresholds can be determined by dividing the GHG emissions inventory goal (allowable emissions), by the estimated 2020 population and employment. This method allows highly efficient projects with higher mass emissions to meet the overall reduction goals of AB 32. Staff believes it is more appropriate to base the land use efficiency threshold on the service population metric for the land use-driven emission inventory. This approach is appropriate because the threshold can be applied evenly to all project types (residential or commercial/retail only and mixed use) and uses only the land use emissions inventory that is comprised of all land use projects. Staff will provide the methodology to calculate a project’s GHG emissions in the revised CEQA Guidelines, such as allowing infill projects up to a 50 percent or more reduction in daily vehicle trips if the reduction can be supported by close proximity to transit and support services, or a traffic study prepared for the project.

<b>Table 6 – California 2020 GHG Emissions, Population Projections and GHG Efficiency Thresholds - Land Use Inventory Sectors</b>	
Land Use Sectors Greenhouse Gas Emissions Target	295,530,000
Population	44,135,923
Employment	20,194,661
California Service Population (Population + Employment)	64,330,584
AB 32 Goal GHG emissions (metric tons CO <sub>2</sub> e)/SP <sup>1</sup>	<b>4.6</b>
Notes: AB = Assembly Bill; CO <sub>2</sub> e = carbon dioxide equivalent; GHG = greenhouse gas; SP = service population.	
<sup>1</sup> Greenhouse gas efficiency levels were calculated using only the “land use-related” sectors of ARB’s emissions inventory.	
Please refer to Appendix D for detailed calculations.	
Sources: Data compiled by EDAW 2009, ARB 2009a, DOF 2009, EDD 2009, ICF Jones & Stokes 2009.	

Staff proposes a project-level efficiency threshold of 4.6 MT CO<sub>2</sub>e/SP, the derivation of which is shown Table 6. This efficiency-based threshold reflects very GHG-efficient projects. As stated previously and below, staff anticipates that significance thresholds (rebuttable presumptions of significance at the project level) will function on an interim basis only until adequate programmatic approaches are in place at the city, county, and regional level that will allow the CEQA streamlining of individual projects. (See Draft CEQA Guidelines, proposed section 15183.5 [“Tiering and Streamlining the Analysis of Greenhouse Gas Emissions”]). In advance of such programmatic approaches, local agencies may wish to apply this efficiency-based recommended threshold with some discretion, taking into account not only the project's efficiency, but also its total GHG emissions. Even where a project is relatively GHG-efficient as compared to other projects, in approving the project, the lead agency is committing to use what is essentially

its GHG "budget" in a given way. Expending this "budget" on the proposed project may affect other development opportunities and associated obligations to mitigate or conflict with other actions that the community may wish to take to reduce its overall GHG emissions after it has conducted its programmatic analysis.

Accordingly, in applying the efficiency-based threshold of 4.6 MT CO<sub>2</sub>e/SP, the lead agency might also wish to consider the project's total emissions. Where a project meets the efficiency threshold but would still have very large GHG emissions, the lead agency may wish to consider whether the project's contributions to climate change might still be cumulatively considerable and whether additional changes to the project or mitigation should be required. Staff notes that even where the project may be significant as it relates to climate change, the lead agency may find that the project should nonetheless be approved in light of its benefits; in that case, the lead agency may wish to note the project's efficiency and any innovative design features in the Statement of Overriding Considerations.

### **2.3.3 PLAN-LEVEL GHG THRESHOLDS**

Staff proposes using a two step process for determining the significance of proposed plans and plan amendments for GHG. As a first step in assessing plan-level impacts, Staff is proposing that agencies that have adopted a qualified climate action plan (or have incorporated similar criteria in their General Plan) and the General Plan or Transportation Plan are consistent with the climate action plan, the General Plan or Transportation Plan would be considered less than significant. In addition, as discussed above for project-level GHG impacts, Staff is proposing an efficiency threshold to assess plan-level impacts. Staff believes a programmatic approach to limiting GHG emissions is appropriate at the plan-level. Thus, as projects consistent with the climate action plan are proposed, they may be able to tier off the plan and its environmental analysis.

#### **2.3.3.1 GHG EFFICIENCY METRICS FOR PLANS**

For local land use plans, a GHG-efficiency metric (e.g., GHG emissions per unit) would enable comparison of a proposed general plan to its alternatives and to determine if the proposed general plan meets AB 32 emission reduction goals.

AB 32 identifies local governments as essential partners in achieving California's goal to reduce GHG emissions. Local governments have primary authority to plan, zone, approve, and permit how and where land is developed to accommodate population growth and the changing needs of their jurisdiction. ARB has developed the Local Government Operations Protocol and is developing a protocol to estimate community-wide GHG emissions. ARB encourages local governments to use these protocols to track progress in reducing GHG emissions. ARB encourages local governments to institutionalize the community's strategy for reducing its carbon footprint in its general plan. SB 375 creates a process for regional integration of land development patterns and transportation infrastructure planning with the primary goal of reducing GHG emissions from the largest sector of the GHG emission inventory, light duty vehicles.

If the statewide AB 32 GHG emissions reduction context is established, GHG efficiency can be viewed independently from the jurisdiction in which the plan is located. Expressing projected 2020 mass of emissions from land use-related emissions sectors by comparison to a demographic unit (e.g., population and employment) provides evaluation of the GHG efficiency of a project in terms of what emissions are allowable while meeting AB 32 targets.

Two approaches were considered for efficiency metrics. The “service population” (SP) approach would consider efficiency in terms of the GHG emissions compared to the sum of the number of jobs and the number of residents at a point in time. The per capita option would consider efficiency in terms of GHG emissions per resident only. Staff recommends that the efficiency threshold for plans be based on all emission inventory sectors because, unlike land use projects, community-wide or regional plans comprise more than just land use related emissions (e.g. industrial). Further, Staff recommends that plan threshold be based on the service population metric as community-wide plans or regional plans include a mix of residents and employees. The Service Population metric would allow decision makers to compare GHG efficiency of general plan alternatives that vary residential and non-residential development totals, encouraging GHG efficiency through improving jobs/housing balance. This approach would not give preference to communities that accommodate more residential (population-driven) land uses than non-residential (employment driven) land uses which could occur with the per capita approach.

A SP-based GHG efficiency metric (see Table 7) was derived from the emission rates at the State level that would accommodate projected population and employment growth under trend forecast conditions, and the emission rates needed to accommodate growth while allowing for consistency with the goals of AB 32 (i.e., 1990 GHG emissions levels by 2020).

<b>Table 7 – California 2020 GHG Emissions, Population Projections and GHG Efficiency Thresholds - All Inventory Sectors</b>	
All Inventory Sectors Greenhouse Gas Emissions Target	426,500,000
Population	44,135,923
Employment	20,194,661
California Service Population (Population + Employment)	64,330,584
AB 32 Goal GHG emissions (metric tons CO <sub>2</sub> e)/SP <sup>1</sup>	<b>6.6</b>
Notes: AB = Assembly Bill; CO <sub>2</sub> e = carbon dioxide equivalent; GHG = greenhouse gas; SP = service population.	
<sup>1</sup> Greenhouse gas efficiency levels were calculated using only the “land use-related” sectors of ARB’s emissions inventory.	
Please refer to Appendix D for detailed calculations.	
Sources: Data compiled by EDAW 2009, ARB 2009a, DOF 2009, EDD 2009, ICF Jones & Stokes 2009.	

If a general plan demonstrates, through dividing the emissions inventory projections (MT CO<sub>2</sub>e) by the amount of growth that would be accommodated in 2020, that it could meet the GHG efficiency metrics proposed in this section (6.6 MT CO<sub>2</sub>e/SP from all emission

sectors, as noted in Table 7), then the amount of GHG emissions associated with the general plan would be considered less than significant, regardless of its size (and magnitude of GHG emissions). In other words, the general plan would accommodate growth in a manner that would not hinder the State's ability to achieve AB 32 goals, and thus, would be less than significant for GHG emissions and their contribution to climate change. The efficiency metric would not penalize well-planned communities that propose a large amount of development. Instead, the SP-based GHG efficiency metric acts to encourage the types of development that BAAQMD and OPR support (i.e., infill and transit-oriented development) because it tends to reduce GHG and other air pollutant emissions overall, rather than discourage large developments for being accompanied by a large mass of GHG emissions. Plans that are more GHG efficient would have no or limited mitigation requirements to help them complete the CEQA process more readily than plans that promote GHG inefficiencies, which will require detailed design of mitigation during the CEQA process and could subject a plan to potential challenge as to whether all feasible mitigation was identified and adopted. This type of threshold can shed light on a well-planned general plan that accommodates a large amount of growth in a GHG-efficient way.

When analyzing long-range plans, such as general plans, it is important to note that the planning horizon will often surpass the 2020 timeframe for implementation of AB 32. Executive Order S-3-05 establishes a more aggressive emissions reduction goal for the year 2050 of 80 percent below 1990 emissions levels. The year 2020 should be viewed as a milestone year, and the general plan should not preclude the community from a trajectory toward the 2050 goal. However, the 2020 timeframe is examined in this threshold evaluation because doing so for the 2050 timeframe (with respect to population, employment, and GHG emissions projections) would be too speculative. Advances in technology and policy decisions at the state level will be needed to meet the aggressive 2050 goals. It is beyond the scope of the analysis tools available at this time to examine reasonable emissions reductions that can be achieved through CEQA analysis in the year 2050. As the 2020 timeframe draws nearer, BAAQMD will need to reevaluate the threshold to better represent progress toward 2050 goals.

### **2.3.4 CLIMATE ACTION PLANS**

Finally, many local agencies have already undergone or plan to undergo efforts to create general or other plans that are consistent with AB 32 goals. The Air District encourages such planning efforts and recognizes that careful upfront planning by local agencies is invaluable to achieving the state's GHG reduction goals. If a project is consistent with an adopted Qualified Climate Action Plan that addresses the project's GHG emissions, it can be presumed that the project will not have significant GHG emission impacts. This approach is consistent with CEQA Guidelines Section 15064(h)(3), which provides that a "lead agency may determine that a project's incremental contribution to a cumulative effect is not cumulatively considerable if the project will comply with the requirements in a previously approved plan or mitigation program which provides specific requirements that will avoid or substantially lessen the cumulative problem."

A qualified Climate Action Plan (or similar adopted policies, ordinances and programs) is one that is consistent with all of the AB 32 Scoping Plan measures and goals. The Climate Action Plan should identify a land use design, transportation network, goals, policies and implementation measures that would achieve AB 32 goals. Plans with horizon years beyond 2020 should consider continuing the downward reduction path set by AB 32 and move toward climate stabilization goals established in Executive Order S-3-05.

#### ***Qualified Climate Action Plans***

A qualified Climate Action Plan adopted by a local jurisdiction should include the following. The District's revised CEQA Guidelines will provide the methodology to determine if a Climate Action Plan meets these requirements.

- ▶ GHG Inventory for Current Year and Forecast for 2020 (and for 1990 if the reduction goal is based on 1990 emission levels).
- ▶ An adopted GHG Reduction Goal for 2020 for the jurisdiction from all sources (existing and future) which is at least one of the following: 1990 GHG emission levels, 15 percent below 2008 emission levels, or 28 percent below BAU Forecasts for 2020 (if including non-land use sector emissions in the local inventory; otherwise can use 26.2 percent if only including land use sector emissions).
- ▶ Identification of feasible reduction measures to reduce GHG emissions for 2020 to the identified target.
- ▶ Application of relevant reduction measures included in the AB 32 Scoping Plan that are within the jurisdiction of the local land use authority (such as building energy efficiency, etc.).
- ▶ Quantification of the reduction effectiveness of each of the feasible measures identified including disclosure of calculation method and assumptions.
- ▶ Identification of implementation steps and financing mechanisms to achieve the identified goal by 2020.
- ▶ Procedures for monitoring and updating the GHG inventory and reduction measures at least twice before 2020 or at least every five years.
- ▶ Identification of responsible parties for Implementation.
- ▶ Schedule of implementation.
- ▶ Certified CEQA document, or equivalent process (see below).

#### ***Local Climate Action Policies, Ordinances and Programs***

Air District staff recognizes that many communities in the Bay Area have been proactive in planning for climate change but have not yet developed a stand-alone Climate Action

Plan that meets the above criteria. Many cities and counties have adopted climate action policies, ordinances and program that may in fact achieve the goals of a qualified climate action plan. Staff recommends that if a local jurisdiction can demonstrate that its collective set of climate action policies, ordinances and other programs is consistent with AB 32, includes requirements or feasible measures to reduce GHG emissions and achieves one of the following GHG emission reduction goals,<sup>3</sup> the AB 32 consistency demonstration should be considered equivalent to a qualified climate action plan:

- ▶ 1990 GHG emission levels,
- ▶ 15 percent below 2008 emission levels, or
- ▶ 28 percent below BAU Forecasts for 2020 (if including non-land use sector emissions in the local inventory; otherwise can use 26.2 percent if only including land use sector emissions).

Qualified Climate Action Plans that are tied to the AB 32 reduction goals would promote reductions on a plan level without impeding the implementation of GHG-efficient development, and would recognize the initiative of many Bay Area communities who have already developed or are in the process of developing a GHG reduction plan. The details required above for a qualified Climate Action Plan (or similar adopted policies, ordinances and programs) would provide the evidentiary basis for making CEQA findings that development consistent with the plan would result in feasible, measureable, and verifiable GHG reductions consistent with broad state goals such that projects approved under qualified Climate Action Plans or equivalent demonstrations would achieve their fair share of GHG emission reductions.

### **2.3.5 STATIONARY SOURCE GHG THRESHOLD**

Staff's recommended threshold for stationary source GHG emissions is based on estimating the GHG emissions from combustion sources for all permit applications submitted to the Air District in 2005, 2006 and 2007. The analysis is based only on CO<sub>2</sub> emissions from stationary sources, as that would cover the vast majority of the GHG emissions due to stationary combustion sources in the SFBAAB. The estimated CO<sub>2</sub> emissions were calculated for the maximum permitted amount, i.e. emissions that would be emitted if the sources applying for a permit application operate at maximum permitted load and for the total permitted hours. All fuel types are included in the estimates. For boilers burning natural gas, diesel fuel is excluded since it is backup fuel and is used only if natural gas is not available. Emission values are estimated before any offsets (i.e., Emission Reduction Credits) are applied. GHG emissions from mobile sources, electricity use and water delivery associated with the operation of the permitted sources are not included in the estimates.

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<sup>3</sup> Lead agencies using consistency with their jurisdiction's climate action policies, ordinances and programs as a measure of significance under CEQA Guidelines section 15064(h)(3) should ensure that the policies, ordinances and programs satisfy all of the requirements of that subsection before relying on them in a CEQA analysis.

It is projected that a threshold level of 10,000 metric tons of CO<sub>2</sub>e per year would capture approximately 95 percent of all GHG emissions from new permit applications from stationary sources in the SFBAAB. That threshold level was calculated as an average of the combined CO<sub>2</sub> emissions from all stationary source permit applications submitted to the Air District during the three year analysis period.

Staff recommends this 10,000 MT of CO<sub>2</sub>/yr as it would address a broad range of combustion sources and thus provide for a greater amount of GHG reductions to be captured and mitigated through the CEQA process. As documented in the Scoping Plan, in order to achieve statewide reduction targets, emissions reductions need to be obtained through a broad range of sources throughout the California economy and this threshold would achieve this purpose. While this threshold would capture 95 percent of the GHG emissions from new permit applications, the threshold would do so by capturing only the large, significant projects. Permit applications with emissions above the 10,000 MT of CO<sub>2</sub>/yr threshold account for less than 10 percent of stationary source permit applications which represent 95 percent of GHG emissions from new permits analyzed during the three year analysis period.

This threshold would be considered an interim threshold and Air District staff will reevaluate the threshold as AB 32 Scoping Plan measures such as cap and trade are more fully developed and implemented at the state level.

### **2.3.6 SUMMARY OF JUSTIFICATION FOR GHG THRESHOLDS**

The bright-line numeric threshold of 1,100 MT CO<sub>2</sub>e/yr is a numeric emissions level below which a project's contribution to global climate change would be less than "cumulatively considerable." This emissions rate is equivalent to a project size of approximately 60 single-family dwelling units, and approximately 59 percent of all future projects and 92 percent of all emissions from future projects would exceed this level. For projects that are above this bright-line cutoff level, emissions from these projects would still be less than cumulatively significant if the project as a whole would result in an efficiency of 4.6 MT CO<sub>2</sub>e per service population or better for mixed-use projects. Projects with emissions above 1,100 MT CO<sub>2</sub>e/yr would therefore still be less than significant if they achieved project efficiencies below these levels. If projects as proposed exceed these levels, they would be required to implement mitigation measures to bring them back below the 1,100 MT CO<sub>2</sub>e/yr bright-line cutoff or within the 4.6 MT CO<sub>2</sub>e Service Population efficiency threshold. If mitigation did not bring a project back within the threshold requirements, the project would be cumulatively significant and could be approved only with a Statement of Overriding Considerations and a showing that all feasible mitigation measures have been implemented. Projects' GHG emissions would also be less than significant if they comply with a Qualified Climate Action Plan.

As explained in the preceding analyses of these thresholds, the greenhouse gas emissions from land use projects expected between now and 2020 built in compliance with these thresholds would be approximately 26 percent below BAU 2020 conditions and thus would be consistent with achieving an AB 32 equivalent reduction. The 26 percent



reduction from BAU 2020 from new projects built in conformance with these proposed thresholds would achieve an aggregate reduction of approximately 1.6 MMT CO<sub>2</sub>e/yr, which is the level of emission reductions from new Bay Area land use sources needed to meet the AB 32 goals, per ARB's Scoping Plan as discussed above.

Projects with greenhouse gas emissions in conformance with these proposed thresholds would therefore not be considered significant for purposes of CEQA. Although the emissions from such projects would add an incremental amount to the overall greenhouse gas emissions that cause global climate change impacts, emissions from projects consistent with these thresholds would not be a "cumulatively considerable" contribution under CEQA. Such projects would not be "cumulatively considerable" because they would be helping to solve the cumulative problem as a part of the AB 32 process.

California's response to the problem of global climate change is to reduce greenhouse gas emissions to 1990 levels by 2020 under AB 32 as a near-term measure and ultimately to 80 percent below 1990 levels by 2050 as the long-term solution to stabilizing greenhouse gas concentrations in the atmosphere at a level that will not cause unacceptable climate change impacts. To implement this solution, the Air Resources Board has adopted a Scoping Plan and budgeted emissions reductions that will be needed from all sectors of society in order to reach the interim 2020 target.

The land-use sector in the Bay Area needs to achieve aggregate emission reductions of approximately 1.6 MMT CO<sub>2</sub>e/yr from new projects between now and 2020 to achieve this goal, as noted above, and each individual new project will need to achieve its own respective portion of this amount in order for the Bay Area land use sector as a whole to achieve its allocated emissions target. Building all of the new projects expected in the Bay Area between now and 2020 in accordance with the thresholds that District staff are proposing will achieve the overall appropriate share for the land use sector, and building each individual project in accordance with the proposed thresholds will achieve that individual project's respective portion of the emission reductions needed to implement the AB 32 solution. For these reasons, projects built in conformance with the proposed thresholds will be part of the solution to the cumulative problem, and not part of the continuing problem. They will allow the Bay Area's land use sector to achieve the emission reductions necessary from that sector for California to implement its solution to the cumulative problem of global climate change. As such, even though such projects will add an incremental amount of greenhouse gas emissions, their incremental contribution will be less than "cumulatively considerable" because they are helping to achieve the cumulative solution, not hindering it. Such projects will therefore not be "significant" for purposes of CEQA. (*See* CEQA Guidelines §15064(h)(1).)

The conclusion that land use projects that comply with these proposed thresholds is also supported by CEQA Guidelines Section 15030(a)(3), which provides that a project's contribution to a cumulative problem can be less than cumulatively considerable "if the project is required to implement or fund its fair share of a mitigation measure or measures designed to alleviate the cumulative impact." In the case of greenhouse gas emissions associated with land use projects, achieving the amount of emission reductions below BAU that will be required to achieve the AB 32 goals is the project's "fair share" of the

overall emission reductions needed under ARB's scoping plan to reach the overall statewide AB 32 emissions levels for 2020. If a project is designed to implement greenhouse gas mitigation measures that achieve a level of reductions consistent with what is required from all new land use projects to achieve the land use sector "budget" – *i.e.*, keeping overall project emissions below 1,100 MT CO<sub>2</sub>e/yr or ensuring that project efficiency is better than 4.6 MT CO<sub>2</sub>e/service population – then it will be implementing its share of the mitigation measures necessary to alleviate the cumulative impact, as shown in the analyses set forth above.

It is also worth noting that this "fair share" approach is flexible and will allow a project's significance to be determined by how well it is designed from a greenhouse-gas efficiency standpoint, and not just by the project's size. For example, a large high-density infill project located in an urban core nearby to public transit and other alternative transportation options, and built using state-of-the-art energy efficiency methods and improvements such as solar panels, as well as all other feasible mitigation measures, would not become significant for greenhouse gas purposes (and thus require a Statement of Overriding Considerations in order to be approved) simply because it happened to be a large project. Projects such as this hypothetical development with low greenhouse-gas emissions per service population are what California will need in the future in order to do its part in achieving a solution to the problem of global climate change. The determination of significance under CEQA should therefore take these factors into account, and staff's proposed significance thresholds would achieve this important policy goal. In all, land use sector projects that comply with the GHG thresholds would not be "cumulatively considerable" because they would be helping to solve the cumulative problem as a part of the AB 32 process.

Likewise, new Air District permit applications for stationary sources that comply with the quantitative threshold of 10,000 MT CO<sub>2</sub>e/yr would not be "cumulatively considerable" because they also would not hinder the state's ability to solve the cumulative greenhouse gas emissions problem pursuant to AB 32. Unlike the land use sector, the AB 32 Scoping Plan measures, including the cap-and-trade program, provide for necessary emissions reductions from the stationary source sector to achieve AB 32 2020 goals.

While stationary source projects will need to comply with the cap-and-trade program once it is enacted and reduce their emissions accordingly, the program will be phased in over time starting in 2012 and at first will only apply to the very largest sources of GHG emissions. In the mean time, certain stationary source projects, particularly those with large GHG emissions, still will have a cumulatively considerable impact on climate change. The 10,000 MT CO<sub>2</sub>e/yr threshold will capture 95 percent of the stationary source sector GHG emissions in the Bay Area. The five percent of emissions that are from stationary source projects below the 10,000 MT CO<sub>2</sub>e/yr threshold account for a small portion of the Bay Area's total GHG emissions from stationary sources and these emissions come from very small projects. Such small stationary source projects will not significantly add to the global problem of climate change, and they will not hinder the Bay Area's ability to reach the AB 32 goal in any significant way, even when considered cumulatively. In Air District's staff's judgment, the potential environmental benefits from

requiring EIRs and mitigation for these projects would be insignificant. In all, based on staff's expertise, stationary source projects with emissions below 10,000 MT CO<sub>2</sub>e/yr will not provide a cumulatively considerable contribution to the cumulative impact of climate change.

### **3 COMMUNITY RISK AND HAZARD THRESHOLDS**

To address community risk from air toxics, the Air District initiated the Community Air Risk Evaluation (CARE) program in 2004 to identify locations with high levels of risk from ambient toxic air contaminants (TAC) co-located with sensitive populations and use the information to help focus mitigation measures. Through the CARE program, the Air District developed an inventory of TAC emissions for 2005 and compiled demographic and health indicator data. According to the findings of the CARE Program, diesel PM—mostly from on and off-road mobile sources—accounts for over 80 percent of the inhalation cancer risk from TACs in the Bay Area (BAAQMD 2006).

The Air District applied a regional air quality model using the 2005 emission inventory data to estimate excess cancer risk from ambient concentrations of important TAC species, including diesel PM, 1,3-butadiene, benzene, formaldehyde and acetaldehyde. The highest cancer risk levels from ambient TAC in the Bay Area tend to occur in the core urban areas, along major roadways and adjacent to freeways and port activity. Cancer risks in areas along these major freeways are estimated to range from 200 to over 500 excess cases in a million for a lifetime of exposure. Priority communities within the Bay Area – defined as having higher emitting sources, highest air concentrations, and nearby low income and sensitive populations – include the urban core areas of Concord, eastern San Francisco, western Alameda County, Redwood City/East Palo Alto, Richmond/San Pablo, and San Jose.

Fifty percent of BAAQMD's population was estimated to have an ambient background inhalation cancer risk of less than 500 cases in one million, based on emission levels in 2005. Table 8 presents a summary of percentages of the population exposed to varying levels of cancer risk from ambient TACs. Approximately two percent of the SFBAAB population is exposed to background risk levels of less than 200 excess cases in one million. This is in contrast to the upper percentile ranges where eight percent of the SFBAAB population is exposed to background risk levels of greater than 1,000 excess cases per one million. To identify and reduce risks from TAC, this chapter presents thresholds of significance for both cancer risk and non-cancer health hazards.

<b>Table 8 – Statistical Summary of Estimated Population-Weighted Ambient Cancer Risk in 2005</b>	
Percentage of Population (Percent below level of ambient risk)	Ambient Cancer Risk (inhalation cancer cases in one million)
92	1,000
90	900
83	800
77	700
63	600
50	500
32	400
13	300
2	200
<1	100

Source: Data compiled by EDAW 2009.

Many scientific studies have linked fine particulate matter and traffic-related air pollution to respiratory illness (Hiltermann et al. 1997, Schikowski et al 2005, Vineis et al. 2007) and premature mortality (Dockery 1993, Pope et al. 1995, Jerrett et al. 2005). Traffic-related air pollution is a complex mix of chemical compounds (Schauer et al. 2006), often spatially correlated with other stressors, such as noise and poverty (Wheeler and Ben-Shlomo 2005). While such correlations can be difficult to disentangle, strong evidence for adverse health effects of fine particulate matter (PM<sub>2.5</sub>) has been developed for regulatory applications in a recent consensus-based study by the California Air Resources Board. This study found that a 10 percent increase in PM<sub>2.5</sub> concentrations increased the non-injury death rate by 10 percent (ARB 2008).

Public Health Officers for four counties in the San Francisco Bay Area in 2009 provided testimony to the Air District’s Advisory Council (February 11, 2009, Advisory Council Meeting on Air Quality and Public Health). Among the recommendations made, was that PM<sub>2.5</sub>, in addition to TACs, be considered in assessments of community-scale impacts of air pollution. In consideration of the scientific studies and recommendations by the Bay Area Health Directors, it is apparent that, in addition to the significance thresholds for local-scale TAC, thresholds of significance are required for near-source, local-scale concentrations of PM<sub>2.5</sub>.

### 3.2 PROPOSED THRESHOLDS OF SIGNIFICANCE

Proposed thresholds of significance and Board-requested options are presented in this section:

- The **Staff Proposal** includes thresholds for cancer risk, non-cancer health hazards, and fine particulate matter.

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- **Board Option 1** includes tiered thresholds for new sources in impacted communities. Thresholds for receptors and cumulative impacts are the same as the Staff Proposal.
- **Board Option 2** removes the option for a qualified Community Risk Reduction Plan from the Staff Proposal.

Proposal/Option	Construction-Related	Operational-Related
<b>Project-Level – Individual Project</b>		
<p><b>Risks and Hazards</b> (Individual Project)</p> <p><u>Staff Proposal</u></p>	<p>Same as Operational Thresholds*</p>	<p><u>All Areas: Siting a New Source or Receptor</u></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;10.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2,5</sub> increase: &gt; 0.3 µg/m<sup>3</sup> annual average</p> <p><u>Zone of Influence:</u> 1,000-foot radius from fence line of source or receptor</p>
<p><b>Risks and Hazards</b> (Individual Project)</p> <p><u>Board Option 1</u></p> <p><b>Tiered Thresholds</b></p>	<p>Same as Operational Thresholds*</p> <hr style="border-top: 1px dashed black;"/> <p>Same as Operational Thresholds*</p>	<p><u>Impacted Communities: Siting a New Source</u></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;5.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2,5</sub> increase: &gt; 0.2 µg/m<sup>3</sup> annual average</p> <p><u>Zone of Influence:</u> 1,000-foot radius from fence line of source or receptor</p> <hr style="border-top: 1px dashed black;"/> <p><u>Impacted Communities: Siting a New Receptor</u> <u>All Other Areas: Siting a New Source or Receptor</u></p> <p>Compliance with Qualified Risk Reduction Plan OR Increased cancer risk of &gt;10.0 in a million Increased non-cancer risk of &gt; 1.0 Hazard Index (Chronic or Acute) Ambient PM<sub>2,5</sub> increase: &gt; 0.3 µg/m<sup>3</sup> annual average</p> <p><u>Zone of Influence:</u> 1,000-foot radius from fence line of source or receptor</p>

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Proposal/Option	Construction-Related	Operational-Related
<b>Risks and Hazards</b> (Individual Project)  <u><b>Board Option 2</b></u>  <b>Quantitative Thresholds</b>	Same as Operational Thresholds*	<u><b>All Areas: Siting a New Source or Receptor</b></u>  Increased cancer risk of >10.0 in a million Increased non-cancer risk of > 1.0 Hazard Index (Chronic or Acute) Ambient PM <sub>2.5</sub> increase: > 0.3 µg/m <sup>3</sup> annual average  <u><b>Zone of Influence:</b></u> 1,000-foot radius from fence line of source or receptor
<b>Accidental Release of Acutely Hazardous Air Pollutants</b>	None	Storage or use of acutely hazardous materials locating near receptors or receptors locating near stored or used acutely hazardous materials considered significant
<b>Project-Level – Cumulative</b>		
<b>Risks and Hazards</b> (Cumulative Thresholds)	Same as Operational Thresholds*	<u><b>All Areas: Siting a New Source or Receptor</b></u>  Compliance with Qualified Risk Reduction Plan OR Cancer: > 100 in a million (from all local sources) Non-cancer: > 1.0 Hazard Index (from all local sources) (Chronic or Acute) <u>PM<sub>2.5</sub>:</u> > 0.8 µg/m <sup>3</sup> annual average (from all local sources)  <u><b>Zone of Influence:</b></u> 1,000-foot radius from fence line of source or receptor
<b>Plan-Level</b>		
<b>Plans</b>	None	1. Overlay zones around existing and planned sources of TACs (including adopted Risk Reduction Plan areas) and odors. 2. Overlay zones of at least 500 feet (or Air District-approved modeled distance) from all freeways and high volume roadways.
<b>Accidental Release of Acutely Hazardous Air Pollutants</b>	None	None

\* Note: The Air District recommends that for construction projects that are less than one year duration, Lead Agencies should annualize impacts over the scope of actual days that peak impacts are to occur, rather than the full year.

### **3.3 JUSTIFICATION AND SUBSTANTIAL EVIDENCE SUPPORTING THRESHOLDS**

The goal of the proposed thresholds is to ensure that no source creates, or receptor endures, a significant adverse impact from any individual project, and that the total of all nearby directly emitted risk and hazard emissions is also not significantly adverse. The thresholds for local risks and hazards from TAC and PM<sub>2.5</sub> are intended to apply to all sources of emissions, including both permitted stationary sources and on- and off-road mobile sources, such as sources related to construction, busy roadways, or freight movement.

Thresholds for an individual new source are designed to ensure that the source does not contribute a cumulatively significant impact. Cumulative thresholds for sources recognize that some areas are already near or at levels of significant impact. If within such an area there are receptors, or it can reasonably be foreseen that there will be receptors, then a cumulative significance threshold sets a level beyond which any additional risk is significant.

For new receptors – sensitive populations or the general public – thresholds of significance are designed to identify levels of contributed risk or hazards from existing local sources that pose a significant risk to the receptors. Single-source thresholds for receptors are provided to recognize that within the area defined there can be variations in risk levels that may be significant. Single-source thresholds assist in the identification of significant risks, hazards, or concentrations in a subarea, within the area defined by the selected radius. Cumulative thresholds for receptors are designed to account for the effects of all sources within the defined area.

Cumulative thresholds, for both sources and receptors, must consider the size of the source area, defined by a radius from the proposed project. To determine cumulative impacts from a prescribed zone of influence requires the use of modeling. The larger the radius, the greater the number of sources considered that may contribute to the modeled risk and, until the radius approaches a regional length scale, the greater the expected modeled risk increment. If the area of impact considered were grown to the scale of a city, the modeled risk increment would approach the risk level present in the ambient air.

#### **3.3.1 SCIENTIFIC AND REGULATORY JUSTIFICATION**

##### ***Regulatory Framework for TACs***

Prior to 1990, the Clean Air Act required EPA to list air toxics it deemed hazardous and to establish control standards which would restrict concentrations of hazardous air pollutants (HAP) to a level that would prevent any adverse effects “with an ample margin of safety.” By 1990, EPA had regulated only seven such pollutants and it was widely acknowledged by that time that the original Clean Air Act had failed to address toxic air emissions in any meaningful way. As a result, Congress changed the focus of regulation in 1990 from a risk-based approach to technology-based standards. Title III, Section 112(b) of the 1990 Clean Air Act Amendment established this new regulatory approach.

Under this framework, prescribed pollution control technologies based upon maximum achievable control technology (MACT) were installed without the a priori estimation of the health or environmental risk associated with each individual source. The law listed 188 HAPs that would be subject to the MACT standards. EPA issued 53 standards for 89 different types of major industrial sources of air toxics and eight categories of smaller sources such as dry cleaners. These requirements took effect between 1996 and 2002. Under the federal Title V Air Operating Permit Program, a facility with the potential to emit 10 tons of any toxic air pollutant, or 25 tons per year of any combination of toxic air pollutants, is defined as a major source HAPs. Title V permits include requirements for these facilities to limit toxic air pollutant emissions.

Several state and local agencies adopted programs to address gaps in EPA's program prior to the overhaul of the national program in 1990. California's program to reduce exposure to air toxics was established in 1983 by the Toxic Air Contaminant Identification and Control Act (AB 1807, Tanner 1983) and the Air Toxics "Hot Spots" Information and Assessment Act (AB 2588, Connelly 1987). Under AB 1807, ARB and the Office of Environmental Health Hazard Assessment (OEHHA) determines if a substance should be formally identified as a toxic air contaminant (TAC) in California. OEHHA also establishes associated risk factors and safe concentrations of exposure.

AB 1807 was amended in 1993 by AB 2728, which required ARB to identify the 189 federal hazardous air pollutants as TACs. AB 2588 (Connelly, 1987) supplements the AB 1807 program, by requiring a statewide air toxics inventory, notification of people exposed to a significant health risk, and facility plans to reduce these risks. In September 1992, the "Hot Spots" Act was amended by Senate Bill 1731 which required facilities that pose a significant health risk to the community to reduce their risk through a risk management plan.

### ***Cancer Risk***

Cancer risk from TACs is typically expressed in numbers of excess cancer cases per million persons exposed over a defined period of exposure, for example, over an assumed 70 year lifetime. The Air District is not aware of any agency that has established an acceptable level of cancer risk for TACs. However, a range of what constitutes a significant increment of cancer risk from any compound has been established by the U.S. EPA. EPA's guidance for conducting air toxics analyses and making risk management decisions at the facility- and community-scale level considers a range of acceptable cancer risks from one in a million to one in ten thousand (100 in a million). The guidance considers an acceptable range of cancer risk increments to be from one in a million to one in ten thousand. In protecting public health with an ample margin of safety, EPA strives to provide maximum feasible protection against risks to health from HAPs by limiting additional risk to a level no higher than the one in ten thousand estimated risk that a person living near a source would be exposed to at the maximum pollutant concentrations for 70 years. This goal is described in the preamble to the benzene National Emissions Standards for Hazardous Air Pollutants (NESHAP) rulemaking (54 Federal Register 38044, September 14, 1989) and is incorporated by Congress for EPA's residual risk program under Clean Air Act section 112(f).



Regulation 2, Rule 5 of the Air District specifies permit requirements for new and modified stationary sources of TAC. The Project Risk Requirement (2-5-302.1) states that the Air Pollution Control Officer shall deny an Authority to Construct or Permit to Operate for any new or modified source of TACs if the project cancer risk exceeds 10.0 in one million.

#### ***Hazard Index for Non-cancer Health Effects***

Non-cancer health hazards for chronic and acute diseases are expressed in terms of a hazard index (HI), a ratio of TAC concentration to a reference exposure level (REL), below which no adverse health effects are expected, even for sensitive individuals. As such, OEHHA has defined acceptable concentration levels, and also significant concentration increments, for compounds that pose non-cancer health hazards. If the HI for a compound is less than one, non-cancer chronic and acute health impacts have been determined to be less than significant.

#### ***State and Federal Ambient Air Quality Standards for PM<sub>2.5</sub>***

The Children's Environmental Health Protection Act (Senate Bill 25), passed by the California state legislature in 1999, requires ARB, in consultation with OEHHA, to "review all existing health-based ambient air quality standards to determine whether, based on public health, scientific literature and exposure pattern data, these standards adequately protect the public, including infants and children, with an adequate margin of safety." As a result of the review requirement, in 2002 ARB adopted an annual average California Ambient Air Quality Standard (CAAQS) for PM<sub>2.5</sub> of 12 ug/m<sup>3</sup> that is not to be exceeded (California Code of Regulations, Title 17 § 70200, Table of Standards.) The National Ambient Air Quality Standard (NAAQS) established an annual standard for PM<sub>2.5</sub> (15 ug/m<sup>3</sup>) that is less stringent than the CAAQS, but also set a 24-hour average standard (35 ug/m<sup>3</sup>), which is not included in the CAAQS (Code of Federal Regulations, Title 40, Part 50.7).

#### ***Significant Impact Levels for PM<sub>2.5</sub>***

EPA recently proposed and documented alternative options for PM<sub>2.5</sub> Significant Impact Levels (SILs) (Federal Register 40 CFR Parts 51 and 52, September 21, 2007). The EPA is proposing to facilitate implementation of a PM<sub>2.5</sub> Prevention of Significant Deterioration (PSD) program in areas attaining the PM<sub>2.5</sub> NAAQS by developing PM<sub>2.5</sub> increments, or SILs. These "increments" are maximum increases in ambient PM<sub>2.5</sub> concentrations (PM<sub>2.5</sub> increments) allowed in an area above the baseline concentration.

The SIL is a threshold that would be applied to individual facilities that apply for a permit to emit a regulated pollutant in an area that meets the NAAQS. The State and EPA must determine if emissions from that facility will cause the air quality to worsen. If an individual facility projects an increase in emissions that result in ambient impacts greater than the established SIL, the permit applicant would be required to perform additional analyses to determine if those impacts will be more than the amount of the PSD increment. This analysis would combine the impact of the proposed facility when added to all other sources in the area.

The EPA is proposing such values for PM<sub>2.5</sub> that will be used as screening tools by a major source subject to PSD to determine the subsequent level of analysis and data gathering required for a PSD permit application for emissions of PM<sub>2.5</sub>. The SIL is one element of the EPA program to prevent deterioration in regional air quality and is utilized in the new source review (NSR) process. New source review is required under Section 165 of the Clean Air Act, whereby a permit applicant must demonstrate that emissions from the proposed construction and operation of a facility “will not cause, or contribute to, air pollution in excess of any maximum allowable increase or maximum allowable concentration for any pollutant.” The purpose of the SIL is to provide a screening level that triggers further analysis in the permit application process.

For the purpose of NSR, SILs are set for three types of areas: Class I areas where especially clean air is most desirable, including national parks and wilderness areas; Class II areas where there is not expected to be substantial industrial growth; and Class III areas where the highest relative level of industrial development is expected. In Class II and Class III areas, a PM<sub>2.5</sub> concentration of 0.3, 0.8, and 1 µg/m<sup>3</sup> has been proposed as a SIL. To arrive at the SIL PM<sub>2.5</sub> option of 0.8 µg/m<sup>3</sup>, EPA scaled an established PM<sub>10</sub> SILs of 1.0 µg/m<sup>3</sup> by the ratio of emissions of PM<sub>2.5</sub> to PM<sub>10</sub> using the EPA’s 1999 National Emissions Inventory. To arrive at the SIL option of 0.3 µg/m<sup>3</sup>, EPA scaled the PM<sub>10</sub> SIL of 1.0 µg/m<sup>3</sup> by the ratio of the current Federal ambient air quality standards for PM<sub>2.5</sub> and PM<sub>10</sub> (15/50). These options represent what EPA currently considers as a range of appropriate SIL values.

EPA interprets the SIL to be the level of PM<sub>2.5</sub> increment that represents a “significant contribution” to regional non-attainment. While SIL options were not designed to be thresholds for assessing community risk and hazards, they are being considered to protect public health at a regional level by helping an area maintain the NAAQS. Furthermore, since it is the goal of the Air District to achieve and maintain the NAAQS and CAAQS at both regional and local scales, the SILs may be reasonably be considered as thresholds of significance under CEQA for local-scale increments of PM<sub>2.5</sub>.

### ***Roadway Proximity Health Studies***

Several medical research studies have linked near-road pollution exposure to a variety of adverse health outcomes impacting children and adults. Kleinman et al. (2007) studied the potential of roadway particles to aggravate allergic and immune responses in mice. Using mice that were not inherently susceptible, the researchers placed these mice at various distances downwind of State Road 60 and Interstate 5 freeways in Los Angeles to test the effect these roadway particles have on their immune system. They found that within five meters of the roadway, there was a significant allergic response and elevated production of specific antibodies. At 150 meters (492 feet) and 500 meters (1,640 feet) downwind of the roadway, these effects were not statistically significant.

Another significant study (Ven Hee et al. 2009) conducted a survey involving 3,827 participants that aimed to determine the effect of residential traffic exposure on two preclinical indicators of heart failure; left ventricular mass index (LVMI), measured by the cardiac magnetic resonance imaging (MRI), and ejection fraction. The studies

classified participants based on the distance between their residence and the nearest interstate highway, state or local highway, or major arterial road. Four distance groups were defined: less than 50 meters (165 feet), 50-100 meters, 101-150 meters, and greater than 150 meters. After adjusting for demographics, behavioral, and clinical covariates, the study found that living within 50 meters of a major roadway was associated with a 1.4 g/m<sup>2</sup> higher LVMI than living more than 150 meters from one. This suggests an association between traffic-related air pollution and increased prevalence of a preclinical predictor of heart failure among people living near roadways.

To quantify the roadway concentrations of PM<sub>2.5</sub> that contributed to the health impacts reported by Kleinman et al (2007), the Air District modeled the emissions and associated particulate matter concentrations for the roadways studied. To perform the modeling, emissions were estimated for Los Angeles using the EMFAC model and annual average vehicle traffic data taken from Caltrans was used in the roadway model (CAL3QHCR) to estimate the downwind PM<sub>2.5</sub> concentrations at 50 meters and 150 meters. Additionally, emissions were assumed to occur from 10:00 a.m. to 2:00 p.m. corresponding to the time in which the mice were exposed during the study. The results of the modeling indicate that at 150 meters, where no significant health effects were found, the downwind concentration of PM<sub>2.5</sub> was 0.78 µg/m<sup>3</sup>, consistent with the proposed EPA SIL option of 0.8 µg/m<sup>3</sup>.

#### ***Concentration-Response Function for PM<sub>2.5</sub>***

In a recent report, ARB reevaluated the relative risk of premature death associated with PM<sub>2.5</sub> exposure based on a review of all relevant scientific literature available, and a new relative risk factor was developed (ARB 2008). This consensus-based review found that a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> concentrations increased the risk of premature death by 10 percent (uncertainty interval: 3 percent to 20 percent) and provides a basis for determining the risk increment from an increase in PM<sub>2.5</sub> concentration. Twelve experts participated in the study to review the literature and develop the concentration response function. The experts were selected through a two-part peer nomination process, designed to obtain a balanced set of views and included experts in epidemiology, toxicology, and medicine.

The methodologies and results presented in this report were endorsed by scientific advisors from Harvard University, OEHHA, and Brigham Young University. The report underwent an external peer review by experts selected through an independent process involving the University of California at Berkeley, Institute of the Environment. The results of the peer review process were incorporated into the report. Subsequent to the peer review, Schwartz et al. (2008) examined the linearity of the concentration-response function of PM<sub>2.5</sub>-mortality and showed that the response function is in agreement with Laden et al. (2006) and, moreover, found that this response function was linear down to background levels.

#### ***San Francisco Ordinance on Roadway Proximity Health Effects***

In 2008, the City and County of San Francisco adopted an ordinance (San Francisco Health Code, Article 38 - Air Quality Assessment and Ventilation Requirement for Urban

Infill Residential Development, Ord. 281-08, File No. 080934, December 5, 2008) requiring that public agencies in San Francisco take regulatory action to prevent future air quality health impacts from new sensitive uses proposed near busy roadways (SFDPH 2008). The regulation requires that developers screen sensitive use projects for proximity to traffic and calculate the concentration of  $PM_{2.5}$  from traffic sources where traffic volumes suggest a potential hazard. If modeled levels of traffic-attributable  $PM_{2.5}$  at a project site exceed an action level (currently set at  $0.2 \mu\text{g}/\text{m}^3$ ) developers would be required to incorporate ventilation systems to remove 80 percent of  $PM_{2.5}$  from outdoor air. The regulation does not place any requirements on proposed sensitive uses if modeled air pollutant levels fall below the action threshold. This ordinance only considers impacts from on-road motor vehicles, not impacts related to construction equipment or stationary sources.

A report with supporting documentation for the ordinance (SFPHD 2008) provided a threshold to trigger action or mitigation of  $0.2 \mu\text{g}/\text{m}^3$  of  $PM_{2.5}$  annual average exposure from roadway vehicles within a 150 meter (492 feet) maximum radius of a sensitive receptor. The report applied the concentration-response function from Jerrett et al. (2005) that attributed 14 percent increase in mortality to a  $10 \mu\text{g}/\text{m}^3$  increase in  $PM_{2.5}$  to estimate an increase in non-injury mortality in San Francisco of about 21 excess deaths per year from a  $0.2 \mu\text{g}/\text{m}^3$  increment of annual average  $PM_{2.5}$ .

#### ***Distance for Significant Impact***

The distance used for the radius around the project boundary should reflect the zone or area over which sources may have a significant influence. For cumulative thresholds, for both sources and receptors, this distance also determines the size of the source area, defined. To determine cumulative impacts from a prescribed zone of influence requires the use of modeling. The larger the radius, the greater the number of sources considered that may contribute to the risk and the greater the expected modeled risk increment. If the area of impact considered were grown to approach the scale of a city, the modeled risk increment would approach the risk level present in the ambient air.

A summary of research findings in ARB's Land Use Compatibility Handbook (ARB 2005) indicates that traffic-related pollutants were higher than regional levels within approximately 1,000 feet downwind and that differences in health-related effects (such as asthma, bronchitis, reduced lung function, and increased medical visits) could be attributed in part to the proximity to heavy vehicle and truck traffic within 300 to 1,000 feet of receptors. In the same summary report, ARB recommended avoiding siting sensitive land uses within 1,000 feet of a distribution center and major rail yard, which supports the use of a 1,000 feet evaluation distance in case such sources may be relevant to a particular project setting. A 1,000 foot zone of influence is also supported by Health & Safety Code §42301.6 (Notice for Possible Source Near School).

Some studies have shown that the concentrations of particulate matter tend to be reduced substantially or can even be indistinguishable from upwind background concentrations at a distance 1,000 feet downwind from sources such as freeways or large distribution centers. Zhu et al. (2002) conducted a systematic ultrafine particle study near Interstate

710, one of the busiest freeways in the Los Angeles Basin. Particle number concentration and size distribution were measured as a function of distances upwind and downwind of the I-710 freeway. Approximately 25 percent of the 12,180 vehicles per hour are heavy duty diesel trucks based on video counts conducted as part of the research. Measurements were taken at 13 feet, 23 feet, 55 feet, 252 feet, 449 feet, and 941 feet downwind and 613 feet upwind from the edge of the freeway. The particle number and supporting measurements of carbon monoxide and black carbon decreased exponentially and all constituents simultaneously tracked with each other as one moves away from the freeway. Ultrafine particle size distribution changed markedly and its number concentrations dropped dramatically with increasing distance. The study found that ultrafine particle concentrations measured 941 feet downwind of I-710 were indistinguishable from the upwind background concentration.

### ***Impacted Communities***

Starting in 2006, the Air District's CARE program developed gridded TAC emissions inventories and compiled demographic information that were used to identify communities that were particularly impacted by toxic air pollution for the purposes of distributing grant and incentive funding. In 2009, the District completed regional modeling of TAC on a one kilometer by one kilometer grid system. This modeling was used to estimate cancer risk and TAC population exposures for the entire District. The information derived from the modeling was then used to update and refine the identification of impacted communities. One kilometer modeling yielded estimates of annual concentrations of five key compounds – diesel particulate matter, benzene, 1,3-butadiene, formaldehyde, and acetaldehyde – for year 2005. These concentrations were multiplied by their respective unit cancer risk factors, as established by OEHHA, to estimate the expected excess cancer risk per million people from these compounds.

Sensitive populations from the 2000 U.S. Census database were identified as youth (under 18) and seniors (over 64) and mapped to the same one kilometer grid used for the toxics modeling. Excess cancers from TAC exposure were determined by multiplying these sensitive populations by the model-estimated excess risk to establish a data set representing sensitive populations with high TAC exposures. TAC emissions (year 2005) were mapped to the one kilometer grid and also scaled by their unit cancer risk factor to provide a data set representing source regions for TAC emissions. Block-group level household income data from the U.S. Census database were used to identify block groups with family incomes where more than 40 percent of the population was below 185 percent of the federal poverty level (FPL). Poverty-level polygons that intersect high (top 50 percent) exposure cells and are within one grid cell of a high emissions cell (top 25 percent) were used to identify impacted areas. Boundaries were constructed along major roads or highways that encompass nearby high emission cells and low income areas. This method identified the following six areas as priority communities: (1) portions of the City of Concord; (2) Western Contra Costa County (including portions of the Cities of Richmond and San Pablo); (3) Western Alameda County along the Interstate-880 corridor (including portions of the Cities of Berkeley, Oakland, San Leandro, San Lorenzo, Hayward; (4) Portions of the City of San Jose. (5) Eastern San Mateo County

(including portions of the Cities of Redwood City and East Palo Alto); and (6) Eastern portions of the City of San Francisco.

### **3.3.2 CONSTRUCTION, LAND USE AND STATIONARY SOURCE RISK AND HAZARD THRESHOLDS**

The proposed options for local risk and hazards thresholds of significance are based on U.S. EPA guidance for conducting air toxics analyses and making risk management decisions at the facility and community-scale level. The thresholds consider reviews of recent health effects studies that link increased concentrations of fine particulate matter to increased mortality. The proposed thresholds would apply to both siting new sources and siting new receptors.

For new sources of TACs, thresholds of significance for a single source are designed to ensure that emissions do not raise the risk of cancer or non-cancer health impacts to cumulatively significant levels. For new sources of PM<sub>2.5</sub>, thresholds are designed to ensure that PM<sub>2.5</sub> concentrations are maintained below state and federal standards in all areas where sensitive receptors or members of the general public live or may foreseeably live, even if at the local- or community-scale where sources of TACs and PM may be nearby.

#### ***Project Radius for Assessing Impacts***

For a project proposing a new source or receptor it is recommended to assess impacts within 1,000 feet, taking into account both its individual and nearby cumulative sources (i.e. proposed project plus existing and foreseeable future projects). Cumulative sources are the combined total risk values of each individual source within the 1,000-foot evaluation zone. A lead agency should enlarge the 1,000-foot radius on a case-by-case basis if an unusually large source or sources of risk or hazard emissions that may affect a proposed project is beyond the recommended radius.

The 1,000 foot radius is consistent with findings in ARB's Land Use Compatibility Handbook (ARB 2005), the Health & Safety Code §42301.6 (Notice for Possible Source Near School), and studies such as that of Zhu et al (2002) which found that concentrations of particulate matter tend to be reduced substantially at a distance 1,000 feet downwind from sources such as freeways or large distribution centers.

#### ***Qualified Community Risk Reduction Plan***

Within the framework of these thresholds, proposed projects would be considered to be less than significant if they are consistent with a qualified Community Risk Reduction Plan (CRRP) adopted by the local jurisdiction with enforceable measures to reduce the community risk. Board Option 2 does not include the CRRP as a significance threshold.

Project proposed in areas where a CRRP has been adopted that are not consistent with the CRRP would be considered to have a significant impact.

Projects proposed in areas where a CRRP has not been adopted and that have the potential to expose sensitive receptors or the general public to emissions-related risk in excess of the thresholds below from any source would be considered to have a significant air quality impact.

The conclusion that land use projects that comply with qualified Community Risk Reduction Plans are less than significant is supported by CEQA Guidelines Sections 15030(a)(3) and 15064(h)(3), which provides that a project's contribution to a cumulative problem can be less than cumulatively considerable if the project is required to implement or fund its fair share of a mitigation measure or measures designed to alleviate the cumulative impact.

***Increased Cancer Risk to Maximally Exposed Individual (MEI)***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of carcinogenic TACs from any source result in an increased cancer risk greater than 10.0 in one million, assuming a 70 year lifetime exposure. Under Board Option 1, within Impacted Communities as defined through the CARE program, the significance level for cancer would be reduced to 5.0 in one million for new sources.

The 10.0 in one million cancer risk threshold for a single source is supported by EPA's guidance for conducting air toxics analyses and making risk management decisions at the facility and community-scale level. It is also the level set by the Project Risk Requirement in the Air District's Regulation 2, Rule 5 new and modified stationary sources of TAC, which states that the Air Pollution Control Officer shall deny an Authority to Construct or Permit to Operate for any new or modified source of TACs if the project risk exceeds a cancer risk of 10.0 in one million.

This threshold for an individual new source is designed to ensure that the source does not contribute a cumulatively significant impact. The justification for the Board Option 1 threshold of 5.0 in one million for new sources in an impacted community is that in these areas the cancer risk burden is higher than in other parts of the Bay Area; the threshold at which an individual source becomes significant is lower for an area that is already at or near unhealthy levels. However, even without a tiered approach, the recommended thresholds already address the burden of impacted communities via the cumulative thresholds: specifically, if an area has many existing TAC sources near receptors, then the cumulative threshold will be reached sooner than it would in another area with fewer TAC sources.

The single-source threshold for receptors is provided to address the possibility that within the area defined by the 1,000 foot radius there can be variations in risk levels that may be significant, below the corresponding cumulative threshold. Single-source thresholds assist in the identification of significant risks, hazards, or concentrations in a subarea, within the 1,000 foot radius.

***Increased Non-Cancer Risk to MEI***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of non-carcinogenic TACs result in an increased chronic or acute Hazard Index (HI) from any source greater than 1.0. This threshold is unchanged under Board Option 1.

A HI less than 1.0 represents a TAC concentration, as determined by OEHHA that is at a health protective level. While some TACs pose non-carcinogenic, chronic and acute health hazards, if the TAC concentrations result in a HI less than one, those concentrations have been determined to be less than significant.

***Increased Ambient Concentration of PM<sub>2.5</sub>***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of PM<sub>2.5</sub> from any source would result in an average annual increase greater than 0.3 µg/m<sup>3</sup>. Under Board Option 1, within Impacted Communities as defined through the CARE program, the significance level for a PM<sub>2.5</sub> increment is 0.2 µg/m<sup>3</sup>.

If one applies the concentration-response function from the ARB consensus review (ARB 2008) and attribute a 10 percent increase in mortality to a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>, one finds an increase in non-injury mortality in the Bay Area of about 20 excess deaths per year from a 0.3 µg/m<sup>3</sup> increment of PM<sub>2.5</sub>. This is consistent with the impacts reported and considered significant by SFDPH (2008) using an earlier study (Jerrett et al. 2005) to estimate the increase in mortality from a 0.2 µg/m<sup>3</sup> PM<sub>2.5</sub> increment.

The SFDPH recommended a lower threshold of significance for multiple sources but only considered roadway emissions within a 492 foot radius. This recommendation applies to a single source but considers all types of emissions within 1,000 feet. On balance, the Air District estimates that the SFDPH threshold and this proposed one, in combination with the cumulative threshold for PM<sub>2.5</sub>, will afford similar levels of health protection.

The proposed PM<sub>2.5</sub> threshold represents the lower range of an EPA proposed Significant Impact Level (SIL). EPA interprets the SIL to be the level of ambient impact that is considered to represent a “significant contribution” to regional non-attainment. While this threshold was not designed to be a threshold for assessing community risk and hazards, it was designed to protect public health at a regional level by helping an area maintain the NAAQS. Since achieving and maintaining state and federal AAQS is a reasonable goal at the local scale, the SIL provides a useful reference for comparison.

This threshold for an individual new source is designed to ensure that the source does not contribute a cumulatively significant impact. The justification for the Board Option 1 threshold of 0.2 µg/m<sup>3</sup> for new sources in an impacted community is that these areas have higher levels of diesel particulate matter than do other parts of the Bay Area; the threshold at which an individual source becomes significant is lower for an area that is already at or near unhealthy levels. However, even without a tiered approach, the recommended thresholds already address the burden of impacted communities via the



cumulative thresholds: specifically, if an area has many existing PM<sub>2.5</sub> sources near receptors, then the cumulative threshold will be reached sooner than it would in another area with fewer PM<sub>2.5</sub> sources.

The single-source threshold for receptors is provided to address the possibility that within the area defined by the 1,000 foot radius there can be variations in risk levels that may be significant, below the corresponding cumulative threshold. Single-source thresholds assist in the identification of significant risks, hazards, or concentrations in a subarea, within the 1,000 foot radius.

### **3.3.2.1 ACCIDENTAL RELEASE OF ACUTELY HAZARDOUS AIR EMISSIONS**

The BAAQMD currently recommends, at a minimum, that the lead agency, in consultation with the administering agency of the Risk Management Prevention Program (RMPP), find that any project resulting in receptors being within the Emergency Response Planning Guidelines (ERPG) exposure level 2 for a facility has a significant air quality impact. ERPG exposure level 2 is defined as "the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action."

Staff proposes continuing with the current threshold for the accidental release of hazardous air pollutants. Staff recommends that agencies consult with the California Emergency Management Agency for the most recent guidelines and regulations for the storage of hazardous materials. Staff proposes that projects using or storing acutely hazardous materials locating near existing receptors, and projects resulting in receptors locating near facilities using or storing acutely hazardous materials be considered significant.

The current Accidental Release/Hazardous Air Emissions threshold of significance could affect all projects, regardless of size, and require mitigation for Accidental Release/Hazardous Air Emissions impacts.

### **3.3.3 CUMULATIVE RISK AND HAZARD THRESHOLDS**

#### ***Qualified Community Risk Reduction Plan***

Proposed projects would be considered to be less than significant if they are consistent with a qualified Community Risk Reduction Plan (CRRP) adopted by the local jurisdiction with enforceable measures to reduce the community risk. Board Option 2 does not include the CCRP as a significance threshold.

Project proposed in areas where a CRRP has been adopted that are not consistent with the CRRP would be considered to have a significant impact.

Projects proposed in areas where a CRRP has not been adopted and that have the potential to expose sensitive receptors or the general public to emissions-related risk in

excess of the following thresholds from the aggregate of cumulative sources would be considered to have a significant air quality impact.

The conclusion that land use projects that comply with qualified Community Risk Reduction Plans are less than significant is supported by CEQA Guidelines Sections 15030(a)(3) and 15064(h)(3), which provides that a project's contribution to a cumulative problem can be less than cumulatively considerable if the project is required to implement or fund its fair share of a mitigation measure or measures designed to alleviate the cumulative impact.

***Increased Cancer Risk to Maximally Exposed Individual (MEI)***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of carcinogenic TACs from any source result in an increased cancer risk greater than 100.0 in one million.

The significance threshold of 100 in a million increased excess cancer risk would be applied to the cumulative emissions. The 100 in a million threshold is based on EPA guidance for conducting air toxics analyses and making risk management decisions at the facility and community-scale level. In protecting public health with an ample margin of safety, EPA strives to provide maximum feasible protection against risks to health from hazardous air pollutants (HAPs) by limiting risk to a level no higher than the one in ten thousand (100 in a million) estimated risk that a person living near a source would be exposed to at the maximum pollutant concentrations for 70 years (NESHAP 54 Federal Register 38044, September 14, 1989; CAA section 112(f)). One hundred in a million excess cancer cases is also consistent with the ambient cancer risk in the most pristine portions of the Bay Area based on the District's recent regional modeling analysis.

***Increased Non-Cancer Risk to MEI***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of non-carcinogenic TACs result in an increased chronic or acute Hazard Index from any source greater than 1.0.

OEHHA has defined acceptable concentration levels for compounds that pose non-cancer health hazards. If the HI for a compound is less than one, non-cancer chronic and acute health impacts have been determined to be less than significant.

***Increased Ambient Concentration of PM<sub>2.5</sub>***

Emissions from a new source or emissions affecting a new receptor would be considered significant where ground-level concentrations of PM<sub>2.5</sub> from any source would result in an average annual increase greater than 0.8 µg/m<sup>3</sup>.

If one applies the concentration-response function from the ARB consensus review (ARB 2008) and attributes a 10 percent increase in mortality to a 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub>, one finds an increase in non-injury mortality in the Bay Area of about 50 excess deaths per year from a 0.8 µg/m<sup>3</sup> increment of PM<sub>2.5</sub>. This is greater the impacts reported and considered significant by SFDPH (2008) using an earlier study (Jerrett et al. 2005) to

estimate the increase in mortality from a  $0.2 \mu\text{g}/\text{m}^3$   $\text{PM}_{2.5}$  increment (SFDPH reported 21 excess deaths per year). However, SFDPH only considered roadway emissions within a 492 foot radius. This proposed threshold applies to all types of emissions within 1,000 feet. In modeling applications for proposed projects, a larger radius results in a greater number of sources considered and higher modeled concentrations. On balance, the Air District estimates that the SFDPH threshold and this proposed one, in combination with the individual source threshold for  $\text{PM}_{2.5}$ , will afford similar levels of health protection.

The proposed cumulative  $\text{PM}_{2.5}$  threshold represents the middle range of an EPA proposed Significant Impact Level (SIL). EPA interprets the SIL to be the level of ambient impact that is considered to represent a “significant contribution” to regional non-attainment. While this threshold was not designed to be a threshold for assessing community risk and hazards, it was designed to protect public health at a regional level by helping an area maintain the NAAQS. Since achieving and maintaining state and federal AAQS is a reasonable goal at the local scale, the SIL provides a useful reference for comparison. Furthermore, the  $0.8 \mu\text{g}/\text{m}^3$  threshold is consistent with studies (Kleinman et al 2007) that examined the potential health impacts of roadway particles.

### **3.3.4 PLAN-LEVEL RISK AND HAZARD THRESHOLDS**

Staff proposes plan-level thresholds that will encourage a programmatic approach to addressing the overall adverse conditions resulting from risks and hazards that many Bay Area communities experience. By designating overlay zones in land use plans, local land use jurisdictions can take preemptive action before project-level review to reduce the potential for significant exposures to risk and hazard emissions. While this will require more up-front work at the general plan level, in the long-run this approach is a more feasible approach consistent with Air District and CARB guidance about siting sources and sensitive receptors that is more effective than project by project consideration of effects that often has more limited mitigation opportunities. This approach would also promote more robust cumulative consideration of effects of both existing and future development for the plan-level CEQA analysis as well as subsequent project-level analysis.

For local plans to have a less-than-significant impact with respect to potential risks and hazards, overlay zones would have to be established around existing and proposed land uses that would emit these air pollutants. Overlay zones to avoid risk impacts should be reflected in local plan policies, land use map(s), and implementing ordinances (e.g., zoning ordinance). The overlay zones around existing and future risk sources would be delineated using the quantitative approaches described above for project-level review and the resultant risk buffers would be included in the General Plan (or the EIR for the General Plan) to assist in site planning. BAAQMD will provide guidance as to the methods used to establish the TAC buffers and what standards to be applied for acceptable exposure level in the updated CEQA Guidelines document. Special overlay zones of at least 500 feet (or an appropriate distance determined by modeling and approved by the Air District) on each side of all freeways and high volume roadways would be included in this proposed threshold.

The threshold of significance for plan impacts could affect all plan adoptions and amendments and require mitigation for a plan's air quality impacts. Where sensitive receptors would be exposed above the acceptable exposure level, the plan impacts would be considered significant and mitigation would be required to be imposed either at the plan level (through policy) or at the project level (through project level requirements).

### **3.3.5 COMMUNITY RISK REDUCTION PLANS**

The goal of a Community Risk Reduction Plan would be to bring TAC and PM<sub>2.5</sub> concentrations for the entire community covered by the Plan down to acceptable levels as identified by the local jurisdiction and approved by the Air District. This approach provides local agencies a proactive alternative to addressing communities with high levels of risk on a project-by-project approach. This approach is supported by CEQA Guidelines Section 15030(a)(3), which provides that a project's contribution to a cumulative problem can be less than cumulatively considerable "if the project is required to implement or fund its fair share of a mitigation measure or measures designed to alleviate the cumulative impact." This approach is also further supported by CEQA Guidelines Section 15064(h)(3), which provides that a project's contribution to a cumulative effect is not considerable "if the project will comply with the requirements in a previously approved plan or mitigation program which provides specific requirements that will avoid or substantially lessen the cumulative problem."

#### ***Qualified Community Risk Reduction Plans***

A qualified Community Risk Reduction Plan adopted by a local jurisdiction should:

- ▶ Include a defined CRRP planning area.
- ▶ Include base year and future year emissions inventories of TACs and PM<sub>2.5</sub>.
- ▶ Establish risk and exposure reduction targets for the community.
- ▶ Identify measures to reduce emissions and exposures.
- ▶ Include Air District–approved risk modeling.
- ▶ Include procedures for monitoring and updating the TAC inventory, modeling and reduction measures, in coordination with Air District staff.
- ▶ Include public participation processes to facilitate community input into goals and strategies.

## 4 CRITERIA POLLUTANT THRESHOLDS

### 4.2 PROPOSED THRESHOLDS OF SIGNIFICANCE

Project Construction	
Pollutant	Average Daily (pounds/day)
ROG (reactive organic gases)	54
NO <sub>x</sub> (nitrogen oxides)	54
PM <sub>10</sub> (exhaust) (particulate matter-10 microns)	82
PM <sub>2.5</sub> (exhaust) (particulate matter-2.5 microns)	54
PM <sub>10</sub> /PM <sub>2.5</sub> (fugitive dust)	Best Management Practices
Local CO (carbon monoxide)	None

Project Operations		
Pollutant	Average Daily (pounds/day)	Maximum Annual (tons/year)
ROG	54	10
NO <sub>x</sub>	54	10
PM <sub>10</sub>	82	15
PM <sub>2.5</sub>	54	10
Local CO	9.0 ppm (8-hour average), 20.0 ppm (1-hour average)	

Plans
<ol style="list-style-type: none"> <li>1. Consistency with Current Air Quality Plan control measures</li> <li>2. Projected VMT or vehicle trip increase is less than or equal to projected population increase</li> </ol>

### 4.3 JUSTIFICATION AND SUBSTANTIAL EVIDENCE SUPPORTING THRESHOLDS

#### 4.3.1 PROJECT CONSTRUCTION CRITERIA POLLUTANT THRESHOLDS

Staff proposes criteria pollutant construction thresholds that add significance criteria for exhaust emissions to the existing fugitive dust criteria employed by the Air District. While our current Guidelines considered construction exhaust emissions controlled by the overall air quality plan, the implementation of new and more stringent state and federal standards over the past ten years now warrants additional control of this source of emissions.

The average daily criteria air pollutant and precursor emission levels shown above are recommended as the thresholds of significance for construction activity for exhaust emissions. These thresholds represent the levels above which a project's individual

emissions would result in a considerable contribution (i.e., significant) to the SFBAAB's existing non-attainment air quality conditions and thus establish a nexus to regional air quality impacts that satisfies CEQA requirements for evidence-based determinations of significant impacts.

For fugitive dust emissions, staff recommends following the current best management practices approach which has been a pragmatic and effective approach to the control of fugitive dust emissions. Studies have demonstrated (Western Regional Air Partnership, U.S.EPA) that the application of best management practices at construction sites have significantly controlled fugitive dust emissions. Individual measures have been shown to reduce fugitive dust by anywhere from 30 percent to more than 90 percent. In the aggregate best management practices will substantially reduce fugitive dust emissions from construction sites. These studies support staff's recommendation that projects implementing construction best management practices will reduce fugitive dust emissions to a less than significant level.

### **4.3.2 PROJECT OPERATION CRITERIA POLLUTANT THRESHOLDS**

The proposed thresholds for project operations are the average daily and maximum annual criteria air pollutant and precursor levels shown above. These thresholds are based on the federal BAAQMD Offset Requirements to ozone precursors for which the SFBAAB is designated as a non-attainment area which is an appropriate approach to prevent further deterioration of ambient air quality and thus has nexus and proportionality to prevention of a regionally cumulative significant impact (e.g. worsened status of non-attainment). Despite non-attainment area for state  $PM_{10}$  and pending nonattainment for federal  $PM_{2.5}$ , the federal NSR Significant Emission Rate annual limits of 15 and 10 tons per year, respectively, are proposed thresholds as BAAQMD has not established an Offset Requirement limit for  $PM_{2.5}$  and the existing limit of 100 tons per year is much less stringent and would not be appropriate in light of our pending nonattainment designation for the federal 24-hour  $PM_{2.5}$  standard. These thresholds represent the emission levels above which a project's individual emissions would result in a cumulatively considerable contribution to the SFBAAB's existing air quality conditions. The thresholds would be an evaluation of the incremental contribution of a project to a significant cumulative impact. These threshold levels are well-established in terms of existing regulations as promoting review of emissions sources to prevent cumulative deterioration of air quality. Using existing environmental standards in this way to establish CEQA thresholds of significance under Guidelines section 15067.4 is an appropriate and effective means of promoting consistency in significance determinations and integrating CEQA environmental review activities with other areas of environmental regulation. (*See Communities for a Better Environment v. California Resources Agency* (2002) 103 Cal. App. 4<sup>th</sup> 98, 111.<sup>4</sup>)

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<sup>4</sup> The Court of Appeal in the *Communities for a Better Environment* case held that existing regulatory standards could not be used as a definitive determination of whether a project would be significant under CEQA where there is substantial evidence to the contrary. Staff's proposed thresholds would not do that. The thresholds are levels at which a project's emissions would normally be significant, but would not be binding on a lead agency if there is contrary evidence in the record.

### **4.3.3 LOCAL CARBON MONOXIDE THRESHOLDS**

The proposed carbon monoxide thresholds are based solely on ambient concentration limits set by the California Clean Air Act for Carbon Monoxide and Appendix G of the State of California CEQA Guidelines.

Since the ambient air quality standards are health-based (i.e., protective of public health), there is substantial evidence (i.e., health studies that the standards are based on) in support of their use as CEQA significance thresholds. The use of the ambient standard would relate directly to the CEQA checklist question. By not using a proxy standard, there would be a definitive bright line about what is or is not a significant impact and that line would be set using a health-based level.

The CAAQS of 20.0 ppm and 9 ppm for 1-hour and 8-hour CO, respectively, would be used as the thresholds of significance for localized concentrations of CO. Carbon monoxide is a directly emitted pollutant with primarily localized adverse effects when concentrations exceed the health based standards established by the California Air Resources Board (ARB).

In addition, Appendix G of the State of California CEQA Guidelines includes the checklist question: Would the project violate any air quality standard or contribute substantially to an existing or projected air quality violation? Answering yes to this question would indicate that the project would result in a significant impact under CEQA. The use of the ambient standard would relate directly to this checklist question.

### **4.3.4 PLAN-LEVEL CRITERIA POLLUTANT THRESHOLDS**

This proposed threshold achieves the same goals as the Air District's current approach while alleviating the existing analytical difficulties and the inconsistency of comparing a plan update with AQP growth projections that may be up to several years old. Eliminating the analytical inconsistency provides better nexus and proportionality for evaluating air quality impacts for plans.

Over the years staff has received comments on the difficulties inherent in the current approach regarding the consistency tests for population and VMT growth. First, the population growth estimates used in the most recent AQP can be up to several years older than growth estimates used in a recent plan update, creating an inconsistency in this analysis. Staff recommends that this test of consistency be eliminated because the Air District and local jurisdictions all use regional population growth estimates that are disaggregated to local cities and counties. In addition, the impact to air quality is not necessarily growth but where that growth is located. The second test, rate of increase in vehicle use compared to growth rate, will determine if planned growth will impact air quality. Compact infill development inherently has less vehicle travel and more transit opportunities than suburban sprawl.

Second, the consistency test of comparing the rate of increase in VMT to the rate of increase in population has been problematic at times for practitioners because VMT is not always available with the project analysis. Staff recommends that either the rate of increase in VMT or vehicle trips be compared to the rate of increase in population. Staff also recommends that the growth estimates used in this analysis be for the years covered by the plan. Staff also recommends that the growth estimates be obtained from the Association of Bay Area Governments since the Air District uses ABAG growth estimates for air quality planning purposes.

## 5 ODOR THRESHOLDS

### 5.2 PROPOSED THRESHOLDS OF SIGNIFICANCE

Project Operations – Source or Receptor	Plans
<ol style="list-style-type: none"> <li>1. More than one confirmed complaint per year averaged over a three year period; or</li> <li>2. More than three unconfirmed complaints per year averaged over a three year period</li> </ol>	<p>Identify (Overlay Zones) and include policies to reduce the impacts of existing or planned sources of odors</p>

### 5.3 JUSTIFICATION AND SUBSTANTIAL EVIDENCE SUPPORTING THRESHOLDS

Staff proposes continuing the current CEQA significance threshold for odors (based on complaint history). The current approach has proven adaptable to different projects and locations and thus continuation of the current approach with more qualitative guidance is considered an appropriate approach to CEQA evaluation.

Odors are generally considered a nuisance, but can result in a public health concern. Some land uses that are needed to provide services to the population of an area can result in offensive odors, such as filling portable propane tanks or recycling center operations. When a proposed project includes the siting of sensitive receptors in proximity to an existing odor source, or when siting a new source of potential odors, the following qualitative evaluation should be performed.

When determining whether potential for odor impacts exists, it is recommended that Lead Agencies consider the following factors and make a determination based on evidence in each qualitative analysis category:

- ▶ **Distance:** Use the screening-level distances in Table 9.



- ▶ **Wind Direction:** Consider whether sensitive receptors are located upwind or downwind from the source for the most of the year. If odor occurrences associated with the source are seasonal in nature, consider whether sensitive receptors are located downwind during the season in which odor emissions occur.
  
- ▶ **Complaint History:** Consider whether there is a history of complaints associated with the source. If there is no complaint history associated with a particular source (perhaps because sensitive receptors do not already exist in proximity to the source), consider complaint-history associated with other similar sources in BAAQMD’s jurisdiction with potential to emit the same or similar types of odorous chemicals or compounds, or that accommodate similar types of processes.
  
- ▶ **Character of Source:** Consider the character of the odor source, for example, the type of odor events according to duration of exposure or averaging time (e.g., continuous release, frequent release events, or infrequent events).
  
- ▶ **Exposure:** Consider whether the project would result in the exposure of a substantial number of people to odorous emissions.

<b>Table 9 – Screening Distances for Potential Odor Sources</b>	
<b>Type of Operation Project Screening</b>	<b>Distance</b>
Wastewater Treatment Plant	2 miles
Wastewater Pumping Facilities	1 mile
Sanitary Landfill	2 miles
Transfer Station	1 mile
Composting Facility	1 mile
Petroleum Refinery	2 miles
Asphalt Batch Plant	2 miles
Chemical Manufacturing	2 miles
Fiberglass Manufacturing	1 mile
Painting/Coating Operations	1 mile
Rendering Plant	2 miles
Food Processing Facility	1 mile
Confined Animal Facility/Feed Lot/Dairy	1 mile
Green Waste and Recycling Operations	1 mile
Coffee Roaster	1 mile

California Integrated Waste Management Board (CIWMB). Facilities that are regulated by the CIWMB (e.g. landfill, composting, etc.) are required to have Odor Impact Minimization Plans (OIMP) in place and have procedures that establish fence line odor detection thresholds. The Air District recognizes a Lead Agency’s discretion under CEQA to use established odor detection thresholds as thresholds of significance for CEQA review for CIWMB regulated facilities with an adopted OIMP.

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# Carbon debt and carbon sequestration parity in forest bioenergy production

STEPHEN R. MITCHELL\*, MARK E. HARMON† and KARI E. B. O'CONNELL†

\*Nicholas School of the Environment, Duke University, Durham, NC 27708, USA, †Department of Forest Ecosystems and Society, College of Forestry, Oregon State University, Corvallis, OR 97331, USA

## Abstract

The capacity for forests to aid in climate change mitigation efforts is substantial but will ultimately depend on their management. If forests remain unharvested, they can further mitigate the increases in atmospheric CO<sub>2</sub> that result from fossil fuel combustion and deforestation. Alternatively, they can be harvested for bioenergy production and serve as a substitute for fossil fuels, though such a practice could reduce terrestrial C storage and thereby increase atmospheric CO<sub>2</sub> concentrations in the near-term. Here, we used an ecosystem simulation model to ascertain the effectiveness of using forest bioenergy as a substitute for fossil fuels, drawing from a broad range of land-use histories, harvesting regimes, ecosystem characteristics, and bioenergy conversion efficiencies. Results demonstrate that the times required for bioenergy substitutions to repay the C Debt incurred from biomass harvest are usually much shorter (< 100 years) than the time required for bioenergy production to substitute the amount of C that would be stored if the forest were left unharvested entirely, a point we refer to as C Sequestration Parity. The effectiveness of substituting woody bioenergy for fossil fuels is highly dependent on the factors that determine bioenergy conversion efficiency, such as the C emissions released during the harvest, transport, and firing of woody biomass. Consideration of the frequency and intensity of biomass harvests should also be given; performing total harvests (clear-cutting) at high-frequency may produce more bioenergy than less intensive harvesting regimes but may decrease C storage and thereby prolong the time required to achieve C Sequestration Parity.

*Keywords:* bioenergy, biofuel, C cycle, C sequestration, forest management

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## Introduction

The search for alternatives to fossil fuel energy has yielded several possibilities, many of which are derived from biomass. Bioenergy has been viewed as a promising alternative to fossil fuels because of its capacity to increase the energy security in regions that lack petroleum reserves and because their production and combustion does not require a net transfer of C from Earth's lithosphere to its atmosphere. While bioenergy is understandably among the most heavily promoted and generously subsidized sources of renewable energy, recent research has brought greater attention to the environmental costs of broad-scale bioenergy production (Fargione *et al.*, 2008; Searchinger *et al.*, 2008, 2009) as well as the limits of how much energy it can actually produce (Field *et al.*, 2008).

One alternative to crop-based biofuels is woody biomass harvested directly from forests, an avenue thought to be more promising than harvesting non-woody species for a variety of reasons. First, woody biomass stores

more potential energy per unit mass than non-woody biomass (Boundy *et al.*, 2011). Second, many forms of non-woody biomass are often utilized following a lengthy conversion process to ethanol or biodiesel, a process which results in a significant loss of potential energy of the harvested biomass (Field *et al.*, 2008) as well as additional energy that may be expended in the conversion process itself (Walker *et al.*, 2010). By contrast, woody biomass is more readily utilized for energy production without any further modifications (Richter *et al.*, 2009). Third, landscapes managed for bioenergy production using woody biomass are able to store more C per unit of land area than crop-based biofuels.

Woody biomass is already a primary source of energy for 2 billion people; the FAO estimates that over half of the world's total round wood removals from forests and trees outside forests are intended for bioenergy production (FAO; Parikka, 2004). Many of these harvests are specifically intended to provide a C-neutral energy source to substitute for fossil fuels (Parikka, 2004; Richter *et al.*, 2009; Buford & Neary, 2010), yet such harvests can arrest the C sequestration of many forests far short of their full potential (Harmon *et al.*, 1990; Canadell & Raupach, 2008; Pan *et al.*, 2011). Much of the world's

Correspondence: Stephen R. Mitchell, tel. + 919 491 0398, fax + 919 684 8741, e-mail: stephen.mitchell@duke.edu

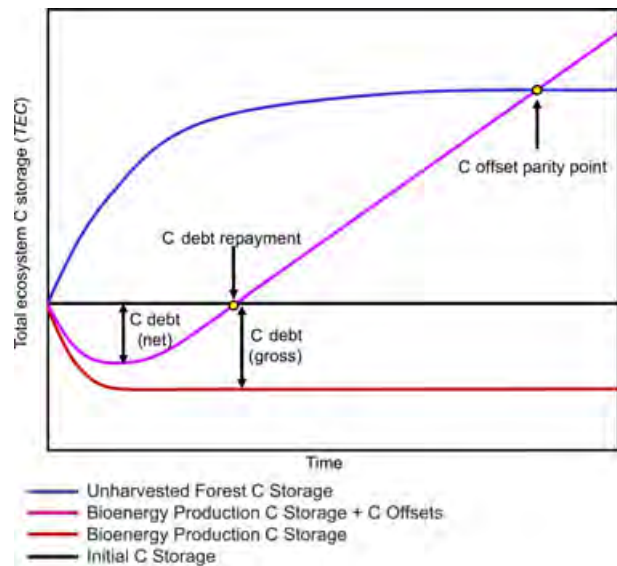


forested land area stores far less C than it potentially could (House *et al.*, 2002; Canadell & Raupach, 2008), and foregoing future harvest/s could provide a more rapid amelioration of atmospheric CO<sub>2</sub> than bioenergy production. A recent study conducted in US West Coast forests examined the C storage/bioenergy production trade-offs of many ecosystems and found that the current C sink for most ecosystems is so strong that it cannot be matched or exceeded through substitution of fossil fuels by forest bioenergy over the next 20 years. However, due to its reliance on existing field data instead of simulation models, it could not extrapolate these results beyond the 20-year period (Hudiburg *et al.*, 2011). Another recent study that addressed these trade-offs is the so-called 'Manomet' study, which modeled bioenergy production systems for different forest types in Massachusetts and found that utilizing forests for bioenergy production reduces C storage without providing an equitable substitution in the near-term (Walker *et al.*, 2010). However, the approach taken by the 'Manomet' study dealt short-term repayment in C Debts at the stand level, while our approach focuses on the C Debt that is incurred as a result harvesting forests for bioenergy production over the long-term at the landscape level. We provide further description of our concept of C Debt *sensu* Fargione *et al.* (2008) by contrasting it with what we refer to as the C Sequestration Parity, which we outline in the discussion below.

### Carbon debt

Compared to fossil fuels, woody biomass yields a lower amount of energy per unit mass of C emitted. Since biomass harvesting reduces C storage but does not produce the same amount of energy that would be obtained from an equal amount of C emissions from fossil fuel combustion, recouping losses in C storage through bioenergy production may require many years. We refer to this recoupage as the *C Debt Repayment*, calculated as the change in C storage resulting from bioenergy harvests and associated C substitution, demonstrated in Fig. 1. A mathematical representation is given below in Eqn (1), where  $C_{\text{storage}(t)}^m$  is the amount of C stored in a managed forest at time  $t$ ,  $C_{\text{storage}(0)}^m$  is the amount of C stored in a managed forest at  $t = 0$  (before bioenergy harvests have begun), and  $C_{\text{harvest}(t)}^m$  is the amount of C biomass harvested from a managed forest at time  $t$ , which is multiplied by the bioenergy conversion factor  $\eta_{\text{biomass}}$ :

$$C_{\text{debt}(t)}^m = C_{\text{storage}(t)}^m - C_{\text{storage}(0)}^m - \sum_{i=1}^n C_{\text{harvest}(t)}^m \times \eta_{\text{biomass}} \quad (1)$$



**Fig. 1** Conceptual representation of C Debt Repayment vs. the C Sequestration Parity Point. C Debt (Gross) is the difference between the initial C Storage and the C storage of a stand (or landscape) managed for bioenergy production. C Debt (Net) is C Debt (Gross) + C substitutions resulting from bioenergy production.

### Carbon sequestration parity

A repayment of the C Debt does not necessarily imply that the forest has been managed for maximal amelioration of atmospheric CO<sub>2</sub>. If a forest is managed for the production of bioenergy to substitute for traditional fossil fuel energy as part of an effort to ameliorate atmospheric CO<sub>2</sub> concentrations, such a strategy should be gauged by the climate change mitigation benefits that would accrue by simply leaving the forest unharvested. Ascertaining the point at which a given strategy provides the maximal amount of climate change mitigation benefits requires accounting for the amount of biomass harvested from a forest under a given management regime, the amount of C stored under a given management regime, and the amount of C that would be stored if the forest were to remain unharvested (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007). It is expected that a forest that is continuously managed for bioenergy production will eventually produce enough bioenergy to 'recoup' the associated loss in C storage (the so-called carbon debt) through the substitution of bioenergy for fossil fuel energy. However, the ultimate effectiveness of this strategy should be determined by the amount of time required for the sum of the total ecosystem C storage and bioenergy C substitution to exceed the amount of C that would be stored if that same forest were to remain unharvested (Fig. 1). We refer to this difference as the C



sequestration differential ( $C_{\text{differential}(t)}^m$ ), illustrated in Eqn (2) below:

$$C_{\text{differential}(t)}^m = C_{\text{storage}(t)}^u - C_{\text{storage}(t)}^m - \sum_{t=1}^n C_{\text{harvest}(t)}^m \times \eta_{\text{biomass}} \quad (2)$$

where  $C_{\text{storage}(t)}^u$  is the amount of C stored in an *unmanaged* forest at time  $t$ . We refer to the crossing of this threshold as the point of *C Sequestration Parity*. Thus, we make a distinction between the amount of time required for the bioenergy production system to recoup any reductions in C storage resulting from bioenergy production (C Debt repayment) and the amount of time required for the bioenergy production system to equal the C than would be stored if the forest were to remain unharvested (C Sequestration Parity Point), as the latter represents a more ambitious climate change mitigation strategy (Fig. 1).

## Materials and methods

We simulated the growth and harvest of woody biomass using a significantly updated version of the ecosystem simulation model LANDCARB (Harmon, 2012). LANDCARB is a landscape-level ecosystem process model that can simulate a full spectrum of potential harvesting regimes while tracking the amount of material harvested, allowing one to simulate ecosystem C storage while tracking the amount of fossil fuel C that could be substituted by using harvested materials as biomass fuels. LANDCARB integrates climate-driven growth and decomposition processes with species-specific rates of senescence and mortality while incorporating the dynamics of inter- and intra-specific competition that characterize forest gap dynamics. Inter- and intra-specific competition dynamics are accounted for by modeling species-specific responses to solar radiation as a function of each species' light compensation point and assuming light is delineated through foliage following a Beer-Lambert function. By incorporating these dynamics the model simulates successional changes as one life-form replaces another, thereby representing the associated changes in ecosystem processes that result from species-specific rates of growth, senescence, mortality, and decomposition.

LANDCARB represents stands on a cell-by-cell basis, with the aggregated matrix of stand cells representing an entire landscape. Each cell in LANDCARB simulates a number of cohorts that represent different episodes of disturbance and colonization within a stand. Each cohort contains up to four layers of vegetation (upper tree layer, lower tree layer, shrub, and herb) that each have up to seven live pools, eight dead pools, and three stable pools. For example, the upper and lower tree layers are comprised of seven live pools: foliage, fine-roots, branches, sapwood, heartwood, coarse-roots, and heart-rot, all of which are transferred to the appropriate dead pool following mortality. Dead sapwood and dead heartwood can be either standing or downed to account for the different microclimates of these positions. Dead pools in a cell can potentially contribute material to three, relatively decay-resistant, stable C pools:

stable foliage, stable wood, and stable soil. There are also two pools representing charcoal (surface and buried).

Our modeling approach with LANDCARB was designed to account for a broad range of ecosystem characteristics and initial landscape conditions of a forest, both of which are influential in determining rate of C debt repayment and the time required for C sequestration parity. Forests with high productivity can generate fossil fuel substitutions more rapidly than forests with low productivity. Conversely, forests with high-longevity biomass raise the C storage of the ecosystem (Olson, 1963), which has implications for C debt and C sequestration parity. Furthermore, forests can contain a wide range of C stores even within a fixed range of productivity and C longevity (i.e., lower rates of mortality and decomposition; Smithwick *et al.*, 2007), yet we know of no study to date that has examined the impact of forest productivity and biomass longevity on C Debt repayment or C Sequestration Parity. Furthermore, we know of no previous study that examines a sufficiently large range of forest management strategies and land-use histories to ascertain exactly what sort of situation/s might provide for an efficient utilization of forest biomass for bioenergy production.

To provide a more comprehensive evaluation of the effectiveness of utilizing forest bioenergy as a substitute for fossil fuels, we performed our analysis across a wide range of ecosystem properties by simulating three levels of forest growth and three levels of biomass longevity, resulting in nine distinct ecosystems (Table 1). Levels of longevity were drawn from published rates of bole growth efficiency, mortality, and decomposition (growth and biomass Harmon *et al.*, 2005). The upper and lower bounds of these parameters were intended to cover the range of these processes for most of the world's temperate forests. Our parameters are largely drawn from forests of the US Pacific Northwest, but the extreme values of bole growth efficiency, mortality, and decomposition could be considered extreme values of other forests as well, thereby giving our results maximal applicability.

We ran each of our nine simulated ecosystems under four sets of initial landscape conditions: afforesting post-agricultural land (age = 0), forest recovering from a severe disturbance (age = 0), old-growth forest (age > 200 years), and a forest harvested on a 50-year rotation (mean age ~25 years). Each combination of ecosystem characteristics and land-use history was simulated with seven different management strategies (Table 2), which included one unharvested control group as well as three biomass harvest frequencies (25, 50, 100 years) applied at two different harvest intensities (50% harvest of live stems, 100% harvest of live stems). We assumed that our post-agricultural landscape did not have any legacy C storage apart from a small amount of soil C, thus our post-agricultural simulation did not have any spin-up simulation. However, simulations of the other land-use histories all had a 500-year spin-up simulation were run to establish initial live, dead, and soil C stores. Additionally, for the two simulations that were recovering from harvests and prior disturbance (recently disturbed and rotation forest) we tracked the respective C stores from these events. To simulate a landscape that had previously been harvested on a 50-year rotation, we simulated an annual clear-cut on 2% of the landscape throughout the 50 years prior to the

**Table 1** Table of selected growth, mortality, and decomposition characteristics for each of our nine ecosystems. Classifications G1, G2, and G3 represent increasing growth rates, represented by the Site Index. L1, L2, and L3 represent increasing biomass longevities. The group with the lowest potential C storage had the lowest growth rate (G1) combined with the highest rates of mortality and decomposition that yielded the lowest rates of biomass longevity (L1). The upper and lower bounds of our rates of growth and longevity were intended to cover the range of these processes for most of the world's forests, thereby giving our results maximal applicability. Thus, the group referred to as G1-L1 is the group with the lowest potential C storage, while the group referred to as G3-L3 has the highest potential C storage. Also note that L1 and L3 values represent extreme values of mortality and decomposition, whereas L2 represents a median value, rather than a midpoint between L1 and L3. Mortality<sub>MAX</sub> is the maximum rate of mortality, while  $k_{\text{Foliage}}$  and  $k_{\text{Heartwood}}$  are decomposition constants for foliage and heartwood. Potential C Storage is the mean amount of C storage of an old-growth stand under these characteristics, as measured over a 500 year interval

Group	Bole growth efficiency + $\Delta$ Mg Stem C/+ $\Delta$ Mg Leaf C)	Mortality <sub>MAX</sub> (yr <sup>-1</sup> )	$k_{\text{Foliage}}$ (yr <sup>-1</sup> )	$k_{\text{Heartwood}}$ (yr <sup>-1</sup> )	Potential C storage (Mg C ha <sup>-1</sup> )
G1-L1	0.35	0.03	0.25	0.1	212
G1-L2	0.35	0.02	0.2	0.02	230
G1-L3	0.35	0.01	0.15	0.01	296
G2-L1	0.54	0.03	0.25	0.1	359
G2-L2	0.54	0.02	0.2	0.02	492
G2-L3	0.54	0.01	0.15	0.01	621
G3-L1	0.84	0.03	0.25	0.1	645
G3-L2	0.84	0.02	0.2	0.02	757
G3-L3	0.84	0.01	0.15	0.01	954

**Table 2** List of all bioenergy production system characteristics simulated. We incorporated four land-use histories, three levels of biomass accumulation, three levels of biomass longevity, three different harvest frequencies and two levels of harvest intensity

Land-use histories	Growth rates	Biomass longevities	Harvest frequencies	Harvest intensities
Post-agricultural (age = 0)	G1*	L1*	100 (100Y)	50% (050H)
Recently disturbed (age = 0)	G2*	L2*	50 (50Y)	100% (100H)
Rotation forest (age ~25)	G3*	L3*	25 (25Y)	
Old-growth (age > 200)				

\*See Table 1 for details.

completion of the spin-up. In accordance with a prior framework for harvested C decomposition, we assumed that 60% of the harvested C would go directly into long-term C storage mediums (i.e., houses, buildings) that decayed at the rate of 1% per year (Harmon & Marks, 2002). The remaining 40% of the harvested C was assumed to be lost to the atmosphere during manufacturing (Harmon & Marks, 2002). Landscapes were first harvested for bioenergy production in the year following the completion of the spin-up.

Initial conditions of our disturbed forest were analogous to those of a severe pine beetle outbreak. To simulate this condition, we initiated a total mortality of all trees at the end of the spin-up, prior to the biomass harvests. We then simulated an annual salvage logging on 5% of the landscape for each of the 5 years following the simulated pine-beetle disturbance (25% of the landscape was salvage logged). We assumed that 75% of all salvageable biomass was removed in each salvage logging. Salvageable materials harvested in the first 5 years following disturbance were assumed to be stored in wood products and subject to the same decomposition scheme outlined above for the 50-year Rotation Harvest. Such conditions are fairly similar to those in a landscape subject to a high-severity, stand-replacing wildfire, though a landscape subject to a pine beetle

infestation will initially have more C storage than one experiencing a high-severity wildfire. However, this difference is temporary and would have a minimal effect on the long-term effects of biomass harvesting, thus this set of initial conditions could also be considered as a proxy for the initial conditions that would follow a high-severity wildfire.

### Wildfire

Our analysis also incorporates wildfires in all simulations, not only because they are naturally occurring phenomena in many forest ecosystems, but also because amount of harvestable biomass in an ecosystem can be altered by the event of wildfire, which needs to be accounted for. In the LANDCARB model, fire severity controls the amount of live vegetation killed and the amount of combustion from the various C pools, and is influenced by the amount and type of fuel present. Fires can increase (or decrease) in severity depending on how much the weighted fuel index a given cell exceeds (or falls short of) the fuel level thresholds for each fire severity class ( $T_{\text{light}}$ ,  $T_{\text{medium}}$ ,  $T_{\text{high}}$  and  $T_{\text{max}}$ ) and the probability values for the increase or decrease in fire severity ( $P_i$  and  $P_d$ ). For example, a low-severity fire may increase to a medium-severity fire if the fuel index

sufficiently exceeds the threshold for a medium-severity fire. Fuel level thresholds were set by monitoring fuel levels in a large series of simulation runs where fires were set at very short intervals to see how low fuel levels needed to be to create a significant decrease in expected fire severity.

The fire regime for low-growth forests (G1) is characterized by a low-severity, high frequency fire regime, with a mean fire return interval (MFRI) of 16 years (Bork, 1985), similar to the fire regime in a Ponderosa pine forest, also a low-growth rate forest. Fire regimes for the medium and high-growth forests (G2, G3) consisted of high-severity, low frequency (MFRI = 250 years) fire regimes, similar to that of a Douglas-fir or Sitka spruce forest (Cissel *et al.*, 1999). We generated exponential random variables to assign the years of fire occurrence (Van Wagner, 1978) based on literature estimates (Bork, 1985) for mean fire return intervals (MFRI) for each ecosystem. The cumulative distribution for our negative exponential function is given in Eqn (1) where  $X$  is a continuous random variable defined for all possible numbers  $x$  in the probability function  $P$  and  $\lambda$  represents the inverse of the expected time for a fire return interval given in Eqn (2).

$$P\{X \leq x\} = \int_0^x \lambda e^{-\lambda x} dx \quad (1)$$

where

$$E[X] = \frac{1}{\lambda} \quad (2)$$

Fire severities in each year generated by this function are cell-specific, as each cell is assigned a weighted fuel index calculated from fuel accumulation within that cell and the respective flammability of each fuel component, the latter of which is derived from estimates of wildfire-caused biomass consumption.

### Bioenergy conversion factors

Previous studies on the mitigation potential of bioenergy have yielded conflicting conclusions about the potential for bioenergy production from woody biomass (Schlamadinger & Marland, 1996a,b,c; Marland & Schlamadinger, 1997; Marland *et al.*, 2007; Walker *et al.*, 2010). Differences in these conclusions are due, in part, to the different assumptions regarding the efficiency of bioenergy utilization. Energy is required for transporting biomass and powering bioenergy conversion facilities, and some is lost due to inefficiencies in the conversion process (Hamelinck *et al.*, 2005; Walker *et al.*, 2010). Thus, it is difficult to provide a one-size-fits-all estimate of bioenergy conversion efficiency. Rather than using one value, we will evaluate a range of bioenergy conversion efficiencies, ranging from 0.2 to 0.8, to ascertain the sensitivity of C offsetting schemes to the range in variability in the energy conversion process. We estimate the *average* bioenergy conversion factor for woody biomass ( $\eta_{biomass}$ ) to be 0.51, meaning that harvesting 1 Mg of biomass C for bioenergy production will substitute for 0.51 Mg fossil fuel C since less energy per unit C emissions is obtainable from biomass compared to fossil fuel. Calculations for this con-

version factor ( $\eta_{biomass}$ ) are in the Supporting Information. A conversion factor of 0.8 represents a highly efficient utilization of bioenergy, though such a conversion efficiency is likely not realistic. Conversely, a conversion factor of 0.2 represents a highly inefficient method of energy utilization, though some bioenergy facilities and conversion processes do operate at this low level of efficiency (Walker *et al.*, 2010).

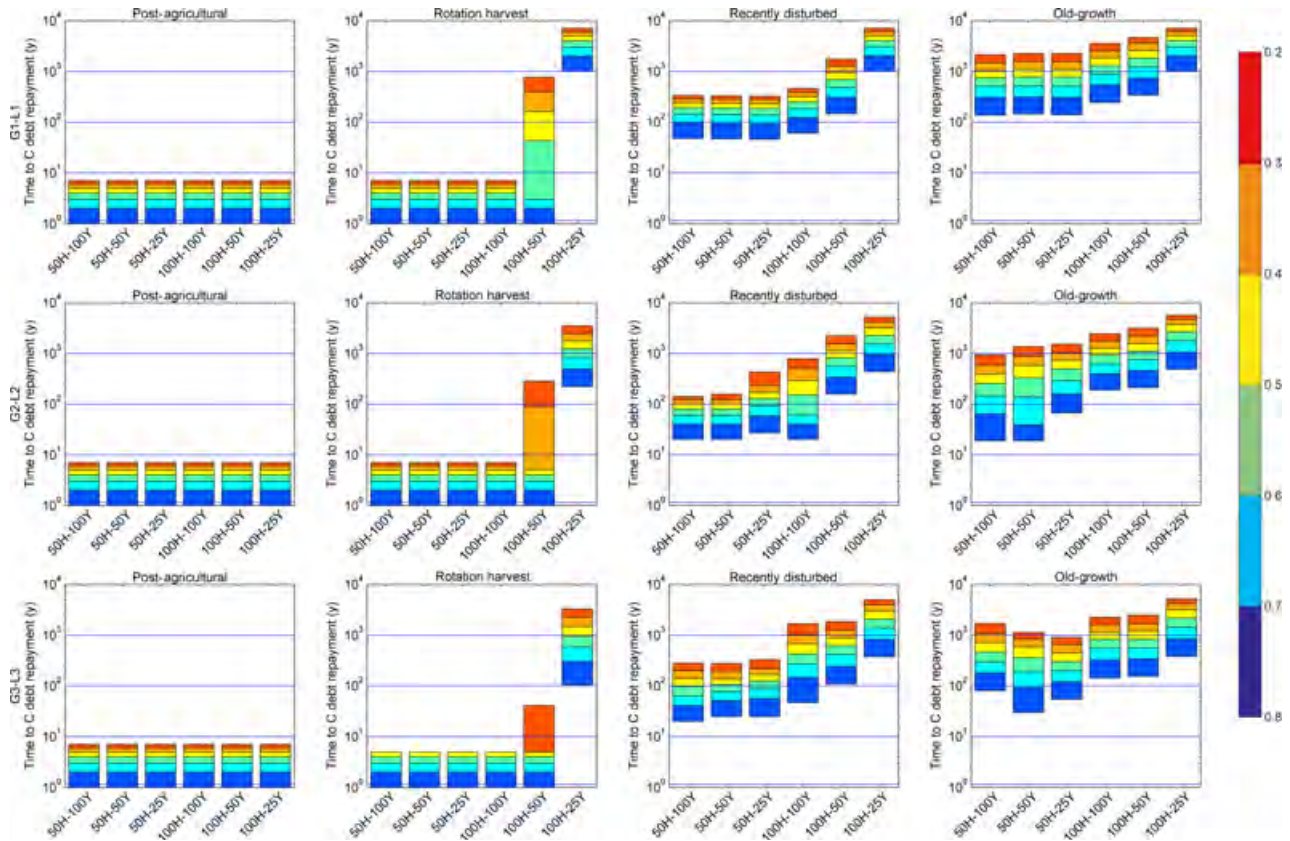
We ran our analysis across 252 distinct scenarios, as we had nine distinct ecosystems (based on three levels of forest growth for three levels of biomass longevity), four initial types of initial landscape conditions, and seven treatment groups (one control, plus three treatment frequencies applied at two levels of intensity). Output from the 252 distinct modeling scenarios was analyzed using seven different bioenergy conversion factors, meaning that our analysis had 1764 combinations of ecosystem properties, initial landscape conditions, harvest frequencies, and bioenergy conversion factors. Our analysis quantifies the degree to which the harvesting and utilization of forest-derived bioenergy alters the landscape-level C storage and bioenergy production in order to calculate (1) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to repay the C Debt incurred from the harvest, and (2) the time required for the C mitigation benefits accrued by forests managed for bioenergy production to achieve C Sequestration Parity, the point at which the sum of forest C storage and bioenergy C substitution equals or exceeds the C mitigation benefits of a comparable forest that remained unharvested.

## Results

### *Times required for repayment of the carbon debts*

Most Post-Agricultural landscapes repaid their C debts within 1 year because their initial live C storages were low to begin with and did not require any waiting period for the repayment of their C Debt (Fig. 2). Thus, by undergoing a conversion from a Post-Agricultural landscape to a bioenergy production landscape, there was a repayment of the C Debt as well as an increase in landscape C storage. Similarly, Rotation Harvest landscapes harvested for bioenergy production every 100 years increased their C storage, as they were previously harvested at a frequency of 50 years. Most of the Rotation Harvest landscapes repaid their C Debt in a year due to their initially low live C storage, as their average stand age is ~25 years. However, some of these landscapes that were clear-cut every 50 or 25 years required much longer to repay their C Debt. Harvesting with greater frequency and intensity lowers C storage and prolongs the time needed for repayment of the C Debt; clear-cut harvests performed on Rotation Harvest landscapes every 25 years required 100 to over 1000 years to repay their C Debt. Once a landscape requires several years to repay its C Debt, it may then exhibit sensitivity to the bioenergy conversion efficiencies used to calculate rate at which it can substitute for C emissions from fossil





**Fig. 2** Comparisons of the time required for a repayment of the C Debt Repayment among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the *x*-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

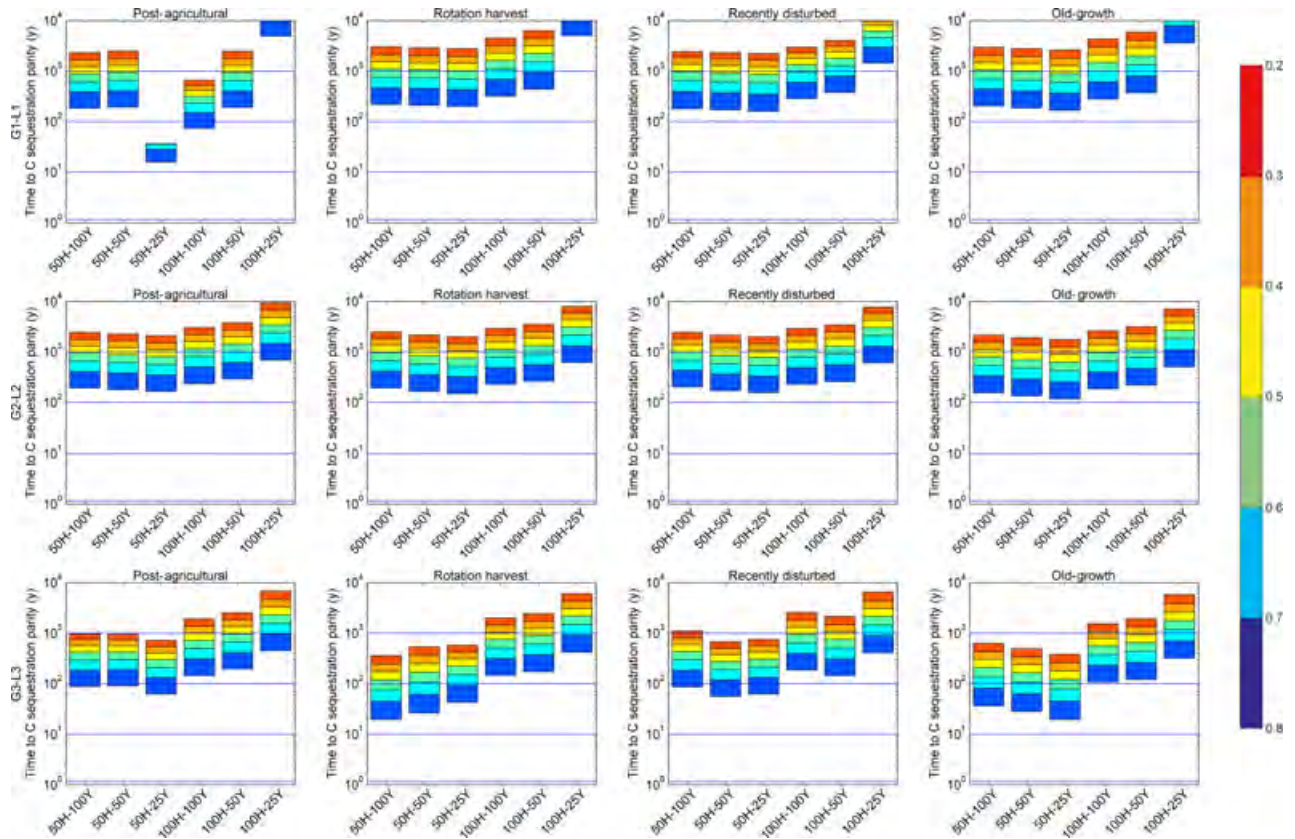
fuels. Recently Disturbed landscapes required more time for a repayment of the C Debt and were much more sensitive to harvest frequency, harvest intensity, and bioenergy conversion efficiencies (Fig. 2). Following disturbance, these landscapes can store high amounts of dead C that can persist for decades. Due to low net primary production following disturbance, recovery to pre-disturbance levels of C storage can take many years, ranging from 20 to over 1000 years. Old-growth landscapes usually took the longest amount of time to repay their C debts because their initial C storages were so high, ranging from 19 to over 1000 years.

#### *Times required to reach carbon sequestration parity*

The amounts of time required for C Sequestration Parity were usually longer than the amounts of time required for a repayment of the C debt. In general, Old-Growth landscapes achieved C Sequestration Parity at a faster rate than other categories of land-use history since they have more initial biomass available

for bioenergy production (Fig. 3). Recently Disturbed landscapes were the second fastest, followed by Rotation Harvest landscapes, though differences between these two categories of land-use history are relatively minor. Post-Agricultural landscapes took longer than the other categories of land-use history, due to a lack of initial biomass available to harvest for bioenergy production.

Times required to reach C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems (Fig. 3), indicating that high productivity ecosystems were able to more quickly recoup their substantial reductions in C storage compared to the rates at which low-productivity ecosystems were able to recoup their considerably smaller reductions in C storage. Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass longevities (L1, L2, L3) on the amount of time required for C Sequestration Parity. Increased biomass longevity (i.e., lower rates of mortality and decomposition) increased



**Fig. 3** Comparisons of the time required for a repayment of the C Sequestration Parity among three of our nine ecosystem types, each with six biomass harvesting regimes and four land-use histories. Note that times are represented on a log scale. Different harvesting regimes are indicated on the x-axis, with 50% and 100% harvesting intensity represented as 50H and 100H, respectively. Harvest frequencies of 25, 50, and 100 years are represented as 25Y, 50Y, and 100Y.

the times required to reach C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity.

Regardless of land-use history and ecosystem characteristics, most scenarios required well over 100 years to reach C Sequestration Parity. Simulations with total harvests performed every 25 years often required more than 1000 years for C Sequestration Parity. Some scenarios achieved C Sequestration Parity in < 50 years, but most of these were scenarios with relatively high bioenergy conversion efficiencies. Harvests performed at lower frequency (50, 100 years) and intensity (50% harvest) required less time; partial harvests (50% harvest) performed every 25 years appeared to reach C Sequestration Parity more rapidly than any other management regime. Harvesting frequency and intensity appeared to affect all ecosystems similarly. Without exception, performing a clear-cut every 25 years resulted in the greatest reduction in C storage and required the longest periods to achieve C Sequestration Parity, suggesting that attempts to generate bioenergy from forests would be most effective in substituting for

fossil fuels when managed for moderate amounts of production over a long time scale.

### Discussion

Delays in the time required for a net benefit of a substitution of bioenergy for fossil fuels are caused by two factors. First, harvesting materials for bioenergy increases the C losses from the forest over the losses caused by mortality and decomposition, thus, increasing the amount of biomass harvest for bioenergy production will increase the C Debt. Second, since there is less potential energy per unit of C emissions in biomass energy compared to fossil fuels, substituting biomass for fossil fuels does not result in a 1 : 1 substitution of energy per unit of C emission. Consequently, ecosystems that are capable of quickly repaying their C Debts were those that had little C storage to begin with.

Our simulations demonstrated that initial landscape conditions and land-use history were fundamental in determining the amount of time required for forests to repay the C Debt incurred from bioenergy production.

While Recently Disturbed and Old-Growth landscapes required considerable time to repay their C Debts, Post-Agricultural and Rotation Harvest landscapes were capable of repaying their C Debt in relatively short time periods, often within 1 year. However, a quick repayment of the C Debt and an increase in C storage does not imply a high degree of bioenergy production; it merely indicates that more C is being stored in a bioenergy production system. Post-Agricultural landscapes undergoing afforestation have minimal initial C storage, and managing them for an appreciable yield of bioenergy production would require a considerable waiting period. Furthermore, the conversion of an agricultural field to a forest could have short-term climatic warming effects while the afforesting landscape is in the early stages of succession, since a decrease in landscape albedo resulting from afforestation could yield climatic warming effects that would overshadow any climatic cooling effects associated with an uptake of atmospheric CO<sub>2</sub> (Jackson *et al.*, 2008; Anderson *et al.*, 2011), as the latter would be relatively small during the early stages of forest succession. By contrast, a Rotation Harvest system would not undergo a significant change in albedo during a transition to a landscape managed for bioenergy production. However, Rotation Harvests have a much different legacy than a Post-Agricultural landscape, since a history of harvesting on the landscape implies that there is additional wood being stored in wood products which are slowly decomposing (see Methods). Consequently, the ongoing decomposition of previously harvested materials lowers terrestrial C storage.

The times required for Old-Growth landscapes to repay C Debt were similar to the times required for them to achieve C Sequestration Parity, since the initial C storage of an old-growth landscape is at or near the level of C that could be stored in the landscape if it were to remain unharvested. Consequently, Old-Growth landscapes required long periods of bioenergy production to achieve C Debt Repayment and C Sequestration Parity. For the three other land-use histories, reaching the point of C Sequestration Parity requires much more time than a repayment of C Debt. Trends were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes and most simulations required at least 100 years to reach C Sequestration Parity (Fig. 3).

Times required for C Sequestration Parity were longest for the low-productivity ecosystems and shortest for the high-productivity ecosystems. Similarly, the effects of biomass longevity were quite consistent among the Recently Disturbed, Rotation Harvest, and Old-Growth landscapes (Fig. 3). Within each respective grouping of ecosystem productivity (G1, G2, G3), there were significant effects of different biomass lon-

gevity rates (L1, L2, L3) on the amount of time required to reach a point of C Sequestration Parity. Higher rates of biomass longevity (i.e., lower rates of mortality and decomposition) resulted in longer times required for C Sequestration Parity, a trend which was consistent across all three rates of ecosystem productivity (Fig. 3). Such a result may seem counterintuitive at first, but the net effect of lowering mortality and decomposition rates is that potential C storage is increased. Since ecosystems with lower mortality and slower decomposition have higher potential C storage, more bioenergy substitutions must be produced to exceed the amount of C stored in a forest that is allowed to grow without harvest. Annual biomass harvest varied little among our different levels of longevity. Therefore, higher rates of biomass longevity raised the target for C Sequestration Parity without resulting in a comparable increase of bioenergy production. We note that biomass longevity is largely a function of the environmental factors that control rates of biomass decomposition, such as temperature and moisture, and is governed by catastrophic disturbances to a lesser degree. Our simulations reiterate previous findings (Mitchell *et al.*, 2009; Campbell *et al.*, 2012) about the limited impact that wildfires have on biomass longevity; wildfires may temporarily lower the C storage of the landscape but most of the losses that occur are among unharvestable components of the forest, such as leaf litter and fine woody debris. Most of the harvestable biomass remains unconsumed even by high-severity wildfires and can either be salvage harvested shortly thereafter or persist on the landscape for decades (Mitchell *et al.*, 2009; Campbell *et al.*, 2012).

However, C storage is not the only way that vegetation affects climate, as different levels of surface reflectance (albedo) and evapotranspiration result in different levels of heat absorbance in the terrestrial biosphere (Jackson *et al.*, 2008; Anderson *et al.*, 2011). Utilizing degraded agricultural lands for the production of bioenergy via non-woody plant species (i.e., switchcane, switchgrass, etc.) could both reduce heat absorbance in the terrestrial biosphere and produce bioenergy to serve as a substitute for fossil fuels. A recent study by Beringer *et al.* (2011) estimated that, by 2050, the cultivation of bioenergy crops on degraded agricultural land could produce 26–116 EJ yr<sup>-1</sup>, 3–12% of projected global energy demand. Additional energy may be obtained from secondary sources, such as residues from agriculture and forestry, municipal solid waste, and animal manures, and the combined production potential could potentially be around 100 EJ yr<sup>-1</sup> by then (Ifeu, 2007; Iea, 2009; Wbgu, 2009; Haberl *et al.*, 2010), thereby generating an additional 10% of projected global energy demand (13–22% total). However, it is unclear what



proportion of degraded agricultural lands would be better utilized for climate change mitigation via reforestation, rather than by non-woody bioenergy production. Non-woody bioenergy crops would need a sufficiently high surface reflectance if their climate change mitigation benefits were to exceed the mitigation benefits of afforestation, but the studies conducted on this topic have yielded conflicting results. Some studies have suggested that land cover types with high albedos could yield a greater cooling to the atmosphere than temperate forests (Diffenbaugh & Sloan, 2002; Oleson *et al.*, 2004; Bala *et al.*, 2007) while other studies have shown the opposite (DeFries *et al.*, 2002; Jackson *et al.*, 2005; Juang *et al.*, 2007), indicating that further research on these tradeoffs is needed.

Further research is also needed to ascertain the potential conversion efficiencies of woody biomass. Our findings indicate that an accounting of the C emissions that are necessary for the harvest, transport, and firing of woody biomass must be performed if forest bioenergy is to be utilized without adding to atmospheric CO<sub>2</sub> concentrations in the near-term. Many of our combinations of forest productivity, biomass longevity and harvesting regimes required more than 100 years to achieve C Sequestration Parity, even when the bioenergy conversion factor was set at near maximal level. A consideration of stand characteristics and land-use history may also prove to be imperative for any bioenergy production system to be effective. Competing land-use objectives make it highly unlikely that forests will be managed purely for C mitigation efforts, and many of the current management objectives within existing forests will undoubtedly prevent them from reaching their full C storage potential. Achieving the maximal C mitigation potential of what remains becomes all the more imperative, as mean global temperatures, sea-level rise, or the melting of ice sheets may continue long after any future stabilization of atmospheric CO<sub>2</sub> and other greenhouse gases (Jones *et al.*, 2009). Managing forests for maximal C storage can yield appreciable, and highly predictable, C mitigation benefits within the coming century, while managing forests for bioenergy production will require careful consideration if they are to provide a C neutral source of energy without yielding a net release of C to the atmosphere in the process.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Figure S1.** Times for Carbon Debt Repayment for all Post-Agricultural landscapes.

**Figure S2.** Times for Carbon Sequestration Parity for all Post-Agricultural landscapes.

**Figure S3.** Times for Carbon Debt Repayment for all Rotation Harvest landscapes.

**Figure S4.** Times for Carbon Sequestration Parity for all Rotation Harvest landscapes.

**Figure S5.** Times for Carbon Debt Repayment for all Recently Disturbed landscapes.

**Figure S6.** Times for Carbon Sequestration Parity for all Recently Disturbed landscapes.

**Figure S7.** Times for Carbon Debt Repayment for all Old-Growth landscapes.

**Figure S8.** Times for Carbon Sequestration Parity for all Old-Growth landscapes.

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## INVITED EDITORIAL

# Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral

ERNST-DETLEF SCHULZE\*, CHRISTIAN KÖRNER†, BEVERLY E. LAW‡, HELMUT HABERL§ and SEBASTIAAN LUYSSAERT¶

\*Max-Planck Institute for Biogeochemistry, Box 100164, 07701, Jena, Germany, †Institute of Botany, University of Basel, 4056, Basel, Switzerland, ‡Department of Forest Ecosystems and Society, Oregon State University, 321 Richardson Hall, Corvallis, OR, USA, §Institute of Social Ecology Vienna, Alpen-Adria University Klagenfurt, Wien, Graz Schottenfeldgasse 29, 1070, Vienna, Austria, ¶Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA CNRS UVSQ, Centre d'Etudes Ormes des Merisiers, 91191, Gif-sur-Yvette, France

## Abstract

Owing to the peculiarities of forest net primary production humans would appropriate ca. 60% of the global increment of woody biomass if forest biomass were to produce 20% of current global primary energy supply. We argue that such an increase in biomass harvest would result in younger forests, lower biomass pools, depleted soil nutrient stocks and a loss of other ecosystem functions. The proposed strategy is likely to miss its main objective, i.e. to reduce greenhouse gas (GHG) emissions, because it would result in a reduction of biomass pools that may take decades to centuries to be paid back by fossil fuel substitution, if paid back at all. Eventually, depleted soil fertility will make the production unsustainable and require fertilization, which in turn increases GHG emissions due to N<sub>2</sub>O emissions. Hence, large-scale production of bioenergy from forest biomass is neither sustainable nor GHG neutral.

**Keywords:** bioenergy, biomass, ecosystem function, forestry, greenhouse gas emission, human appropriation of net primary production

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Climate change impacts resulting from fossil fuel combustion challenge humanity to find energy alternatives that would reduce greenhouse gas (GHG) emissions. One important option in this context is bioenergy. There is a wealth of literature on actual yields of different energy crops and production systems (WBGU, 2009; NRC, 2011). Beringer *et al.* (2011) estimate that 15–25% of global primary energy could come from bioenergy in the year 2050. A prominent recent assessment suggested that bioenergy provision could even be up to 500 EJ yr<sup>-1</sup>, more than current global fossil energy use (Chum *et al.*, 2012) and that GHG mitigation could be sustained under future climate conditions (Liberloo *et al.*, 2010).

Western and developing countries are on a course to increase bioenergy production substantially. For example, the United States enacted the Renewable Fuels Standard as part of the 2005 Energy Policy Act and amended it in 2007, mandating the use of renewable fuels for transportation from 2008 to 2022 and beyond.

In addition, 20% of all EU energy consumption is to come from renewable sources by 2020 with bioenergy as a focal point in this effort (COM, 2006a). In 2005, the European Commission adopted the Biomass Action Plan (COM, 2005) and in 2006 the Strategy for Biofuels (COM, 2006b), both of which aim to increase the supply and demand for biomass. Strategies that could substantially diminish our dependence on fossil fuels without competing with food production include substitution with bioenergy from forests (Tilman *et al.*, 2009), either by direct combustion near the source or by conversion to cellulosic ethanol. There are important questions about GHG reduction, economic viability, sustainability and environmental consequences of these actions.

## Greenhouse gas reduction

The general assumption that bioenergy combustion is carbon-neutral is not valid because it ignores emissions due to decreasing standing biomass and contribution to the land-based carbon sink. The notion of carbon-neutrality is based on the assumption that CO<sub>2</sub> emissions from bioenergy use are balanced by plant growth, but

Correspondence: Ernst-Detlef Schulze, tel. + 49 3641 576 100, fax + 49 3641 577 102, e-mail: dschulze@bgc-jena.mpg.de

this reasoning makes a 'baseline error' by neglecting the plant growth and consequent C-sequestration that would occur in the absence of bioenergy production (Searchinger, 2010; Hudiburg *et al.*, 2011), and it ignores the fact that fossil fuels are needed for land management, harvest and bioenergy processing.

Recent life cycle assessments cast doubt on the existence of emission savings of bioenergy substitution from forests. In the Pacific Northwest United States, policies are being developed for broad-scale thinning of forests for bioenergy production, with the assumed added benefit of minimizing risk of crown fires. This includes forests of all ages and thus timeframes of biomass accumulation. However, a recent study suggests that more carbon would be harvested and emitted in fire risk reduction than would be emitted from fires (Hudiburg *et al.*, 2011). Furthermore, policies allow thinning of mesic forests with long fire return intervals, and removal of larger merchantable trees to make it economically feasible for industry to remove the smaller trees for bioenergy. These actions would lead to even larger GHG emissions beyond those of contemporary forest practices (Hudiburg *et al.*, 2011).

Increased GHG emissions from bioenergy use are mainly due to consumption of the current carbon pool and from a permanent reduction of the forest carbon stock resulting from increased biomass harvest (Holtmark, 2011). When consumption exceeds growth, today's harvest is carbon that took decades to centuries to accumulate and results in a reduction of biomass compared to the current biomass pool (Holtmark, 2011; Hudiburg *et al.*, 2011). Hence, it is another example of 'slow in and fast out' (Körner, 2003). Consequently, reduction in forest carbon stocks has been shown to at least cancel any GHG reductions from less use of fossil fuel over decadal time spans (Haberl *et al.*, 2003; McKechnie *et al.*, 2011). Boreal forests with relatively low carbon sequestration potential may take centuries before permanent reduction of the carbon stocks resulting from increased bioenergy harvest is repaid by reduced emissions from fossil fuels (Holtmark, 2011). For more productive temperate regions, an infinite payback time was found implying that lower GHG emissions are achieved through C-sequestration in forests rather than through bioenergy production (Hudiburg *et al.*, 2011).

Recent studies of the differences in timing of CO<sub>2</sub> emissions from bioenergy production and forest carbon uptake (Cherubini *et al.*, 2011a,b) suggest that the 'upfront' CO<sub>2</sub> emitted during biomass harvest and combustion stays in the atmosphere for decades before the CO<sub>2</sub> is removed by the growing forest. It results in a 'pulse' of warming in the first decades of bioenergy implementation. This contrasts calls for a rapid reduction of the growth rate of climate forcing (Friedlingstein

*et al.*, 2011) required to achieve the policy of limiting warming to 2 °C.

The initially reported emission savings from forest bioenergy are based on erroneous assumptions in the accounting schemes. Studies that corrected these errors suggest that forest management that reduces the current biomass pool is unlikely to result in the envisioned emissions savings at all, and certainly not over the next decades.

### Economic viability

Emerging technologies such as biofuel refineries and combined heat and power plants have to compete against established technologies applied in coal, gas and nuclear power plants. In the United States, a recent National Research Council report concluded that only in an economic environment characterized by high oil prices (e.g. >\$191 per barrel), technological breakthroughs (cellulosic ethanol) and at a high implicit or actual carbon price would biofuels be cost-competitive with petroleum-based fuel (NRC, 2011). Hence, incentives favouring bioenergy (i.e. production quota, subsidies, tax cuts) will be needed to complement or even replace fossil fuel-based technologies (Schneider & Kaltschmitt, 2000; Ryan *et al.*, 2006; Ahtikoski *et al.*, 2008; NRC, 2011).

Schemes favouring the economics of one practice or technology over another often lead to unanticipated side-effects. For example, side-effects have been documented for the Common Agricultural Policy of the European Union (Macdonald *et al.*, 2000; Stoate *et al.*, 2001), and forest-based bioenergy production would seem to be similar. In Germany, where bioenergy is subsidized, the market price for woody biomass increased from 8 to 10 € m<sup>-3</sup> in 2005 to 46 € m<sup>-3</sup> for hardwood and 30–60 € m<sup>-3</sup> for coniferous wood in 2010. Prices for woody biomass for bioenergy now reach 60–70% of saw log prices (Waldbesitzerverband, 2010; wood sales by one of the authors). Such prices discourage the production of quality timber and make root extraction and total tree use attractive options despite the documented unfavourable effects on soil carbon, soil water and nutrient management (Johnson & Todd, 1998; Johnson & Curtis, 2001; Burschel & Huss, 2009; Peckham & Gower, 2011).

For the German example, the price increase is driven by the installation of distributed bioenergy plants and the competitive market of other uses for biomass, such as wood for production of cellulose. Although the details will differ among regions and countries, increasing imports by developed nations is the most likely response to an increasing wood demand (Seintsch, 2010), because total wood harvest has not substantially changed in the developed world (i.e.  $\sim 1.4 \times 10^9$  m<sup>3</sup>

between 1990 and 2010 in Europe and North America, FAO, 2010). Increased imports are likely to be met through land-use (intensity) change in other regions (lateral transfer of emissions). In the case of increased imports, these are most likely met by harvesting previously unmanaged forests or forest plantations. Thus, similar to crop-based production systems, forest-based bioenergy requires additional land, contrary to previous expectations (Tilman *et al.*, 2009). Increased wood imports, thus, represent a global footprint of local energy policies and should be accounted for in life cycle assessment of wood-based bioenergy.

Reduced manufacturing residue losses and other technological advances such as glued wood-based elements initiated a trend towards shorter rotations and thus younger forests. However, the economics of bioenergy production supported by existing subsidy schemes is expected to reduce rotation length to its lowest limit and promote questionable management practices and increased dependency on wood imports. Further, high prices for biomass will discourage forest owners from investments in long rotations, resulting in a shortage of quality timber. Given the time required to produce high-quality timber, such shortage cannot be remedied by short-term (economic) incentives.

### Environmental consequences

Homogeneous young stands with a low biomass resulting from bioenergy harvest are less likely to serve as habitat for species that depend on structural complexity. It is possible that succession following disturbance can lead to young stands that have functional complexity analogous to that of old forests; however, this successional pathway would likely occur only under natural succession (Donato *et al.*, 2011). A lower structural complexity, and removal of understory species, is expected to result in a loss of forest biodiversity and function. It would reverse the trend towards higher biomass of dead wood (i.e. the Northwest Forest Plan in the United States) to maintain the diversity of xylobiontic species.

Cumulative impacts of bioenergy-related management activities that modify vegetation, soil and hydrologic conditions are likely to influence erosion rates and flooding and lead to increased annual runoff and fish habitat degradation of streams (Elliot *et al.*, 2010). Young uniform stands with low compared to high standing biomass have less aesthetic value for recreation (Tahvanainen *et al.*, 2001) and are less efficient in avalanche control and slope stabilization in mountains owing to larger and more frequent cutting (Brang, 2001). A potential advantage is that younger forests with shorter rotations offer opportunities for assisted migration, although there is great uncertainty in

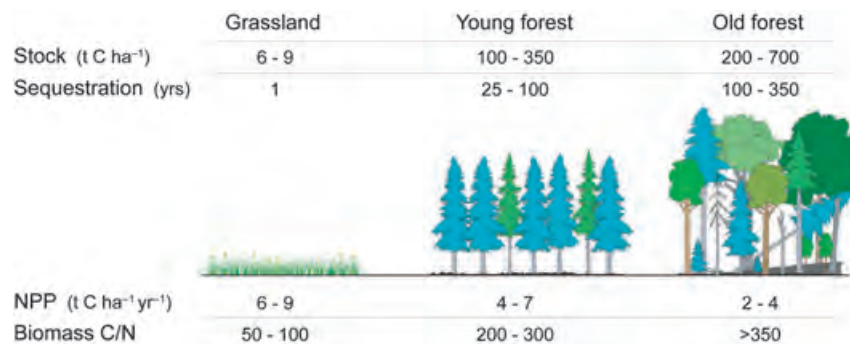
winners and losers (species, provenances, genotypes) in a future climate (Larsen, 1995; Millar *et al.*, 2007; Pedlar *et al.*, 2011). Plantations, however, largely contribute to pathogen spread, such as rust disease (Royle & Hubbes, 1992).

Forests offer several important ecosystem services in addition to biomass and some would be jeopardized by the bioenergy-associated transition from high to low standing biomass. Agriculture provides a visible example for abandoning most ecosystem services except biomass production (Foley *et al.*, 2005); communities in intensive agricultural regions often rely on (nearby) forested water sheds for drinking water, recreation and offsetting GHG emissions from intensive agriculture (Schulze *et al.*, 2009).

### Sustainability

From a historical perspective, a transition from forest biomass burning to fossil fuels literally fuelled the industrial revolution, and consequently, caused rapid climate change. However, the collapse of biomass use enabled the recovery of largely degraded forest ecosystems (Gingrich *et al.*, 2007). Partly due to recovery from previous (mis)use, C-sequestration is especially strong over Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the United States (Williams *et al.*, 2011). As such, C-sequestration can be considered a side-effect of the transition of energy sources from wood to fossil fuels (Erb *et al.*, 2008). Industrial-scale use of forest biomass for energy production would likely reverse this trend or at least reduce the carbon sink strength of forests (Haberl *et al.*, 2003; Holtmark, 2011; Hudiburg *et al.*, 2011). The historical forest resource use in Europe and the United States is the present day situation in Africa. For example, southern African *miombo* forests have been degraded into shrubland as a result of charcoal production, where charcoal is the main energy source for rural communities even at a very low level of total energy consumption (Kutsch *et al.*, 2011).

A widespread misconception is that the most productive forests are necessarily the strongest carbon sinks. Actually, net primary productivity of forests is typically negatively correlated with the cumulative amount of carbon stored in biomass (Fig. 1). In reality, old forests show lower NPP but store the largest amount of carbon (Luyssaert *et al.*, 2008; Hudiburg *et al.*, 2009; Bugmann & Bigler, 2011) because slow growing forest live longer than fast growing forest (Schulman, 1954; Bigler & Veblen, 2009). Hence, on areas currently forested, any fast rotation management and use for fossil fuel substitution is reducing forest carbon sequestration. At regional scales, a permanent increase in annual wood harvest results in a permanent reduction in the amount of



**Fig. 1** Land management trade-off: maximizing productivity vs. carbon stocks. Given fixed resource availability, land managers can maintain highly productive ecosystems with a low standing biomass such as grasslands. The dominant tissues are leaves and roots with a low C/N ratio (~50). The same resources could be used to grow forest. With time forest accumulate considerable amounts of carbon in their biomass but forest that grow old have a lower net primary production than young forest and grasslands. Woody biomass has high C/N ratios (~400) and with an increasing share of woody biomass in the total biomass, the C/N ratio of the ecosystem decreases. Consequently, the time integral of productivity will be lower for an old forest compared with grassland, but at the same time, the time integral of nitrogen export will be lower for an old forest (closed nitrogen cycle) compared with a grassland (open nitrogen cycle). Hence, increasing the biomass pool size is the sustainable way of capitalizing from forests in the C-sequestration vs. C substitution debate. Ranges in the figure are for temperate ecosystems based on (Van Tuyl *et al.*, 2005; Luyssaert *et al.*, 2007, 2008; Schulze *et al.*, 2009; Keith *et al.*, 2009).

carbon stored in forests at the regional scale due to a lower average stand age (Körner, 2009; Holtmark, 2011).

Globally, ~7% of global forest net primary production (NPP) outside wilderness areas is used by humans annually (Haberl *et al.*, 2007a). In Europe, human appropriation of forest NPP reaches ~15% (Luyssaert *et al.*, 2010). Thus, even in the absence of industrial production of wood-based bioenergy, humans already seize a remarkable share of forest production. To produce 20% of current primary energy consumption from wood-based bioenergy, as suggested by policy targets, it

would require more than doubling the global human appropriation of NPP (HANPP) to 18–21% (Table 1; ratio of row 1 and 6). Such an increase in human appropriation would have serious consequences for global forests. Due to its nature, much of forest NPP cannot be harvested, e.g. fine root NPP, NPP for mycorrhizal associations and NPP in volatile organic emissions. Further, forests are harvested after decades of growth; hence, much of the NPP is already consumed by herbivores, added to the litter pool or decomposed in the detritus food chains long before harvest, e.g. leaves, fruits, fine

**Table 1** Global HANPP in forests in the year 2000 and future HANPP that would result from providing 20% of world primary energy from forest harvest. NPP denotes net primary production and HANPP the human appropriation of net primary production. Using a gross caloric value of 19 kJ g<sup>-1</sup> forest biomass or 38 kJ g<sup>-1</sup> biomass carbon and a net caloric value of 41.9 GJ for 1 ton of oil equivalent. Conversion from net to gross caloric value was based on the following multipliers (gross/net): coal 1.1, oil 1.06, natural gas 1.11 and biomass 1.1 (Haberl *et al.*, 2006)

	Global C-flux (PgC yr <sup>-1</sup> )	Energy equivalent (EJ yr <sup>-1</sup> )	Source
(1) Current NPP of forest ecosystems	27–29	1030–1100	Haberl <i>et al.</i> (2007a) and Pan <i>et al.</i> (2011)
(1a) Belowground NPP (40%)	10–11	–	Luyssaert <i>et al.</i> (2007)
(1b) Leaf + twigs NPP (30%)	8.4–8.7	–	Luyssaert <i>et al.</i> (2007)
(1c) Aboveground woody NPP (30%)	8.4–8.7	330	Luyssaert <i>et al.</i> (2007)
(2) Primary energy use in 2006–2008	–	550	IEA (2008) and BP (2009)
(3) Global fossil energy use in 2006–2008	6–7	450	IEA (2008) and BP (2009)
(4) Additional fuel wood to produce 20% of primary energy	2.3	87	From 3 and 5
(5) NPP lost in harvest (10–30%)	0.5–1.4	19–53	From 2 and 6
(6) New HANPP level in forests	4.4–5.3	170–200	From 2, 6 and 7



roots, mycorrhiza and plants in early succession stages. Last, part of the NPP could be harvested but typically has no economic value, e.g. perennials, mosses and lichens. Consequently, the maximum HANPP is about 30% of the total NPP; hence, the proposed HANPP of 18–21% already represents ca. 60% of the global increment of woody biomass (Table 1; ratio of rows 1c and 6). Note that our maximum level of harvestable increment of woody biomass is most likely overestimated because the estimate did not account for economic (e.g. distance to population centre), logistic (e.g. steep mountain slopes) and legal (e.g. conservation areas) constraints on harvest. In addition to the increased GHG emissions that would result from such a programme due to reduced biomass stocks (see above), this increase in human appropriation of forest production would likely contribute to forest biodiversity loss, according to recent evidence on the correlation between HANPP and species richness (Haberl *et al.*, 2005, 2007b).

Typically, the most fertile lands are in urban and agricultural use (Scott *et al.*, 2001), leaving the poorer soils for forest use. The industrial-scale of envisioned forest bioenergy production would export substantial amounts of nutrients, further depleting the soil nutrient stock, particularly if wood removal includes relatively nutrient-rich biomass residues (slash) and root stocks (Peckham & Gower, 2011) as for total tree use. Nutrient and cation losses would have to be compensated for by fertilization, which in turn increases GHG emissions and increases N and P levels in nearby rivers leading to eutrophication of aquatic ecosystems (for a crop related example see Secchi *et al.*, 2011).

A persistent 60–70% appropriation of woody biomass increment for bioenergy production from forest harvest over decades will erode current biomass pools, lower average stand age, deplete soil fertility and could thus only be sustained by amendments to nitrogen and phosphorous-depleted soils, activities that also produce GHG (N<sub>2</sub>O) emissions.

## Conclusion

Although bioenergy from forest harvest could supply ~20% of current energy consumption, this would increase human appropriation of NPP in forests to ~20% which is equivalent to 60–70% of the global increment in woody biomass. We argue that the scale of such a strategy will result in shorter rotations, younger forests, lower biomass pools and depleted soil nutrient capital. This strategy is likely to miss its main objective to reduce GHG emissions because depleted soil fertility requires fertilization that would increase GHG emissions, and because deterioration of current biomass pools requires decades to centuries to be paid back by

fossil fuel substitution, if paid back at all. Further, shorter rotations would simplify canopy structure and composition, impacting ecosystem diversity, function and habitat. In our opinion, reasonable alternatives are afforestation of lands that once carried forests and allowing existing forests to provide a range of ecosystem services. Yet, on arable or pasture land, such a strategy would compete with food and fodder production. Society should fully quantify direct and indirect GHG emissions associated with energy alternatives and associated consequences prior to making policy commitments that have long-term effects on global forests. Reasonable alternatives for reducing GHG emissions on the order of the proposed bioenergy substitution include increased energy efficiency and reduced waste of energy via technological improvements and behaviour modification. There is a substantial risk of sacrificing forest integrity and sustainability for maintaining or even increasing energy production with no guarantee to mitigate climate change.

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# Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels

JON MCKECHNIE,<sup>†</sup> STEVE COLOMBO,<sup>‡</sup> JIAXIN CHEN,<sup>‡</sup> WARREN MABEE,<sup>§</sup> AND HEATHER L. MACLEAN<sup>\*†,||</sup>

*Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario M5S 1A4, Canada, Ontario Forest Research Institute, 1235 Queen Street East, Sault Ste. Marie, Ontario P6A 2E5, Canada, School of Policy Studies and Department of Geography, Queen's University, 423-138 Union St. Kingston, Ontario K7L 3N6, Canada, and Department of Chemical Engineering & Applied Chemistry, School of Public Policy and Governance, University of Toronto, Toronto, Ontario M5S 1A4, Canada*

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The potential of forest-based bioenergy to reduce greenhouse gas (GHG) emissions when displacing fossil-based energy must be balanced with forest carbon implications related to biomass harvest. We integrate life cycle assessment (LCA) and forest carbon analysis to assess total GHG emissions of forest bioenergy over time. Application of the method to case studies of wood pellet and ethanol production from forest biomass reveals a substantial reduction in forest carbon due to bioenergy production. For all cases, harvest-related forest carbon reductions and associated GHG emissions initially exceed avoided fossil fuel-related emissions, temporarily increasing overall emissions. In the long term, electricity generation from pellets reduces overall emissions relative to coal, although forest carbon losses delay net GHG mitigation by 16–38 years, depending on biomass source (harvest residues/standing trees). Ethanol produced from standing trees increases overall emissions throughout 100 years of continuous production: ethanol from residues achieves reductions after a 74 year delay. Forest carbon more significantly affects bioenergy emissions when biomass is sourced from standing trees compared to residues and when less GHG-intensive fuels are displaced. In all cases, forest carbon dynamics are significant. Although study results are not generalizable to all forests, we suggest the integrated LCA/forest carbon approach be undertaken for bioenergy studies.

## Introduction

Forests can contribute to greenhouse gas (GHG) mitigation strategies through capturing and storing atmospheric CO<sub>2</sub> in live biomass, dead organic matter, and soil pools, supplying a source for wood products that both stores carbon and can

displace more GHG-intensive alternatives, and providing a feedstock for bioenergy to displace fossil fuel use. While the merit of each of these options has been individually investigated, trade-offs associated with forest resource utilization decisions must also be considered. Of particular interest is the relationship between harvest and forest carbon storage and how this impacts the GHG mitigation performance of forest products, including bioenergy. Existing tools employed to evaluate emissions associated with different forest resource use decisions are not individually well suited to considering such interactions.

Life cycle assessment (LCA) has been applied to bioenergy options, including electricity generation and transportation fuels. The GHG mitigation potential of bioenergy products depends on activities throughout the entire life cycle (LC), making such a perspective necessary for a comprehensive evaluation. Numerous LCAs have focused on agricultural biomass as feedstock for bioenergy, e.g., reviewed in ref (1). Comparatively few LCAs have evaluated bioenergy from forest biomass; those that have examined electricity generation (e.g., ref (2)), heating (e.g., ref (3)), and transportation (e.g., ref (4)). Bioenergy LCAs have generally found that the substitution of fossil fuel-derived energy with biomass-derived alternatives reduces GHG emissions, owing in part to the assumption that biomass-based CO<sub>2</sub> emissions do not increase atmospheric CO<sub>2</sub>.

Conventional wisdom has generally accepted this assumption of biomass 'carbon neutrality', and thus, most of the LC GHG emissions associated with bioenergy production are attributed to fossil carbon inputs into the system (5). In practice, however, the assumption of carbon neutrality may not accurately represent carbon cycling related to biomass growth (e.g., ref (6)). The practice of annual or semiannual harvest in agriculture means that carbon uptake by biomass may reasonably match carbon release in bioenergy systems within a short time frame, although land use change impacts resulting from biomass production can upset this balance (7). In temperate forests, the harvest cycle can range from 60 to 100 or more years due to the relatively slow growth of forest species. It could therefore take a century for carbon stocks to be replaced, particularly under a clearcutting regime (harvest of all merchantable trees). Harvest patterns and associated implications for forest carbon stocks vary extensively, ranging from clearcuts to variable retention patterns, including shelterwood and selection cuts. Some variable retention approaches may actually increase forest regeneration, increasing the potential to recover carbon (8). Bioenergy production from harvest residues (tree tops and branches) also impacts forest carbon stocks; left uncollected, residues continue to store carbon until released by decomposition or treatment for forest regeneration. While sustainable forest management should ensure that harvest does not impair the long-term productivity of forests, harvest and other forest management activities clearly impact present and future forest carbon stocks. LCA, in its current form, is not well suited to consider the complexities of forest carbon dynamics.

Forest carbon studies have weighed the carbon balance of harvest with the GHG mitigation potential of forest products (e.g., refs 9–11). Some studies have utilized sophisticated forest carbon models to track changes in carbon stored in living biomass (above ground and below ground), dead organic matter, and soil pools (e.g., refs 12, 13). These studies, however, generally employ simplified assumptions regarding the GHG emissions of forest products (including bioenergy) and have not incorporated a full LC approach. Given the dependence of emissions on specific system

\* Corresponding author phone: (416) 946-5056, fax: (416) 978-3674, e-mail: hmaclean@ecf.utoronto.ca.

<sup>†</sup> Department of Civil Engineering, University of Toronto.

<sup>‡</sup> Ontario Forest Research Institute.

<sup>§</sup> Queen's University.

<sup>||</sup> School of Public Policy and Governance, University of Toronto.



characteristics (e.g., biomass source, bioenergy production process, fuel displaced), generalized assumptions regarding the GHG mitigation potential of bioenergy are inadequate for informing decision making and public policies.

State-of-the-art tools are available for independently evaluating both the LC emissions of bioenergy systems and forest carbon dynamics. Using these methods in isolation, as has been general practice, stops short of the comprehensive evaluation needed to properly assess the GHG emissions of forest products. In an assessment of GHG mitigation performance of structural wood products, ref (14) incorporated LCA with an analysis of forest carbon dynamics. While the study did not consider bioenergy as a product, the results illustrate the importance of considering forest carbon and LC emissions simultaneously when evaluating forest products. Applied to bioenergy, integrating LCA with forest carbon modeling would improve understanding of potential contributions to climate change mitigation.

Bioenergy has been treated inconsistently across energy and climate change policy initiatives in terms of how (or if) GHG emissions are quantified. Forest bioenergy policies that ignore carbon flows in the forest may prove ineffective at achieving actual emissions reductions (15). Exclusion of forest carbon from current initiatives is in part due to data issues, although emerging guidelines may ameliorate this situation (16). Tools that are able to synthesize forest carbon data and LCA and evaluate trade-offs between bioenergy and forest carbon remain to be developed.

Forest bioenergy has the potential to significantly reduce GHG emissions compared with fossil fuel alternatives. However, interactions between biomass harvest and forest carbon and the resulting effect on the GHG mitigation performance of bioenergy systems are inadequately understood. The objectives of this study are to demonstrate the integration of LCA and forest carbon modeling to assess the total GHG emissions (referred to as “emissions”) of forest-based bioenergy options and to determine how emissions reductions associated with bioenergy are impacted when forest carbon is taken into account. We demonstrate this approach through a case study investigating two bioenergy products (wood pellets, referred to as pellets, and ethanol) from two biomass sources (standing trees and harvest residues, referred to as residues) within the Great Lakes–St. Lawrence (GLSL) forest region of Ontario, Canada.

## Methods

We develop a framework integrating two analysis tools: life cycle inventory (LCI) analysis and forest carbon modeling. See Supporting Information for additional detail on all methods. LCI analysis quantifies emissions related to the production and use of forest biomass-derived energy. The LCI is based on the assumption of immediate biomass carbon neutrality, as is common practice, and is therefore employed to quantify the impact of all emissions on atmospheric GHGs with the exception of biomass-based CO<sub>2</sub>.

Forest carbon modeling quantifies the impact of biomass harvest on forest carbon dynamics, permitting an evaluation of the validity of the immediate carbon neutrality assumption. If biomass-based CO<sub>2</sub> is fully compensated for by forest regrowth, biomass harvest will have no impact on forest carbon stocks. Reduced forest carbon indicates that a portion of biomass-based CO<sub>2</sub> emissions contributes to increased atmospheric GHGs and should be attributed to the bioenergy pathway. The total emissions associated with a bioenergy system are the sum of the two sets of GHG flows (those resulting from the LCI and those from the forest carbon analysis)

$$\text{GHG}_{\text{Tot}}(t) = \Delta\text{FC}(t) + \text{GHG}_{\text{Bio}}(t) \quad (1)$$

where  $\text{GHG}_{\text{Tot}}(t)$  is the total emissions associated with bioenergy,  $\Delta\text{FC}(t)$  is the change in forest carbon due to biomass harvest for bioenergy, and  $\text{GHG}_{\text{Bio}}(t)$  is the GHG emissions associated with bioenergy substitution for a fossil fuel alternative [all reported in metric tonne CO<sub>2</sub> equivalent (tCO<sub>2</sub>equiv)] at time  $t$ .

The change in forest carbon,  $\Delta\text{FC}(t)$ , is the difference in forest carbon stocks between harvest scenarios: those ‘with’ and ‘without’ bioenergy production. While we present this as a single parameter in eq 1, in reality forest carbon models consider the complexity of carbon fluxes between pools within the forest and between the forest and atmosphere. Carbon in biomass harvested for bioenergy is assumed to be immediately released to the atmosphere. However, forest regrowth will capture and store atmospheric CO<sub>2</sub> over time. There is therefore a time dependency to the carbon impact of forest harvest for bioenergy. Assessing the change in forest carbon requires consideration of the forest response following harvest and the fate of the biomass source if it is not harvested for bioenergy (standing trees could be harvested for other uses or never harvested; residues could decompose on site, be burned as part of site preparation, or be collected for other uses). Local conditions influence such factors and must inform specific applications of this method. Information relevant to the current case study is provided in the following methods subsection.

LCI quantifies emissions associated with all activities from initial resource extraction and fuel production through to the use of fuels, inclusive of transportation and distribution stages. Emissions related to the production of inputs are included based on their cradle-to-grave activities. Comparing emissions of a bioenergy product with the relevant reference fossil fuel alternative(s) determines the bioenergy GHG mitigation performance. The output of the bioenergy LCI models, emissions per functional unit, is not directly compatible with the output of forest carbon models, which quantify carbon stocks over relatively long time periods (e.g., 100 years) in order to fully capture the impact of management decisions. To integrate the assessment tools, we quantify the cumulative emissions associated with bioenergy production within the time period investigated with the forest carbon model (e.g., 100 years), considering GHG mitigation from fossil fuel displacement to be permanent. LCI results are converted to a quantity of emissions by

$$\text{GHG}_{\text{Bio}}(t) = \int_0^t Q_i(t) \times \text{GHG}_i \, dt \quad (2)$$

where  $\text{GHG}_{\text{Bio}}(t)$  represents emissions associated with bioenergy substitution for fossil fuel alternative(s) at time  $t$  (tCO<sub>2</sub>equiv),  $Q_i(t)$  is the quantity of biomass used to produce bioenergy product  $i$  at time  $t$  (e.g., oven dry tonne (odt) biomass/year), and  $\text{GHG}_i$  is the emissions associated with bioenergy product  $i$  per unit biomass (tCO<sub>2</sub>equiv/odt). Summing the bioenergy emissions (based on the LCI results) and the forest carbon emissions gives the total emissions of bioenergy utilization over time as shown in eq 1.

Considering emissions over a long time period is relevant to the carbon dynamics of a forest; however, this introduces uncertainty regarding future forest conditions, markets, and the performance of the energy systems investigated. The LCI and forest carbon analysis in this research consider that these conditions remain static throughout the time frame due to the difficulty of deriving reasonable estimates for these parameters. These issues are further examined in the Results and Discussion.

**Application of LCI/Forest Carbon Model framework.** We apply the above framework to investigate the impact of forest carbon dynamics on the total emissions associated with several forest-based bioenergy pathways. Forest biomass is assumed to be procured for the production of fuels for



electricity generation and light-duty vehicle (LDV) transportation. Reference models are also developed for conventional fuel sources to which the bioenergy pathways are compared. We examine emissions of selected GHGs (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O), reported as CO<sub>2</sub>equiv based on 100 year global warming potentials (17). See the Supporting Information for additional case study details and data.

The pathways considered are as follows. (1) Electricity generation: (a) Reference coal: production of electricity from coal at an existing generating station (GS) in Ontario; (b) Pellet cofiring, harvest residue: production of electricity at 20% cofiring rate (energy input basis) at retrofit coal GS, pellets produced from residues; (c) Pellet cofiring, standing tree: production of electricity at 20% cofiring rate (energy input basis) at a retrofit coal GS, pellets produced from standing trees. (2) Transportation: (a) Reference gasoline: gasoline use in LDV; (b) E85, harvest residue: ethanol/gasoline blended fuel use in LDV, ethanol produced from residues (biomass is not pelletized); (c) E85, standing tree: ethanol/gasoline blended fuel (85% ethanol by volume) use in LDV, ethanol produced from standing trees (biomass is not pelletized).

**Biomass Sources.** Biomass is supplied from standing trees and residues from 5.25 million hectares within the GLSL forest region in Ontario. This area represents 19% of provincially owned forest managed for timber production. Trees allocated for harvest that are not currently utilized for traditional products could serve as a source of biomass for bioenergy applications without impacting markets for conventional wood products. Residues do not have a useful purpose in the region's conventional forest products industry and are left to decompose in the forest. Competition for limited wood resources can result in diversion from current uses (e.g., pulp) to bioenergy (18) with potential indirect emissions consequences (7). By limiting the present study to biomass sources unutilized for conventional products, we avoid such market interactions.

Standing tree harvest and related forest operations (regeneration, road construction/maintenance, and transport to the pellet/ethanol facility) are assessed using a model developed in our previous work (6). Emissions related to residue collection are calculated by treating the residues as a byproduct of forest harvest. Only additional fuel use required for collection beyond that of current harvest operations is allocated to the residues; other forest operations are allocated to the primary forest product and are therefore not included in the present study. Residue collection consists of roadside chipping and loading.

**Electricity Pathways.** LCI models representing electricity generation from coal and cofiring of pellets from standing trees were developed in our prior work (6). The models consider emissions associated with the full fuel LCs from initial resource extraction through to combustion as well as upstream emissions related to process inputs. One kWh is selected as the functional unit for the analysis. We assume that pellet production from residues and their use for cofiring is similar to that of pellets from standing trees but modify the pelletization process to reflect that residues are chipped in the forest (standing trees are delivered as logs). For both sources, 15% of input biomass is assumed to be consumed during pellet production to dry the biomass. Avoiding fossil fuel use reduces emissions during the pelletization process but increases biomass input to pellet production and associated forest carbon impacts. Implications of this assumption are considered in Results and Discussion.

**Transportation Pathways.** Ethanol production, transportation, distribution, and use as E85 fuel in LDV are modeled based on the wood-to-ethanol biochemical conversion pathway in the Government of Canada's "well-to-wheel" model, GHGenius 3.17 (4). The gasoline portion of

E85 fuel and the reference gasoline pathway are also taken from GHGenius. The functional unit for the transportation pathways is 1 km driven. Significant uncertainty exists in evaluating ethanol production from cellulosic feedstock as technological development and optimization is ongoing and production not yet at commercial scale (19).

**Forest Carbon.** The forest carbon dynamics related to biomass harvest are evaluated using FORCARB-ON, an Ontario-specific adaptation of the FORCARB2 model (12). FORCARB-ON quantifies carbon stocks (in living trees, soil, standing dead trees, down dead wood, forest floor, and understory vegetation pools) based on harvest schedules and inventories that producers are required to report to the Province. Harvest schedules take into account species and age composition of the forest, age classes eligible for harvest, natural disturbance frequency, growth rates, and forest succession. The model estimates forest carbon stocks over 100 years, a time frame relevant to the long-term perspective of forest management planning.

We evaluate forest carbon stocks for three potential harvest scenarios: (1) "current harvest" baseline, where biomass (standing trees, residues) is not collected for bioenergy production and therefore timber is removed solely to satisfy the current demand for traditional wood products; (2) "current + residue" harvest, with residue removal for bioenergy production; and (3) "maximum allowable" harvest, with additional standing tree harvest (compared to the baseline) for bioenergy production (residues are not collected). The difference in forest carbon stocks between the bioenergy production scenarios and "current harvest" baseline scenario is allocated to the bioenergy products. Additional standing tree harvest for bioenergy occurs as scheduled under forest management plans; following harvest, stands are regenerated by planting or natural regeneration, varying by site. If not harvested for bioenergy, standing trees eventually undergo natural succession and are subject to a small likelihood of natural disturbance. Residue collection is assumed to not impact soil carbon stocks; uncollected residues are assumed to decompose on site, either at the roadside or near where trees were felled. The consequence of collecting residues for bioenergy production is that this temporary carbon store is 'liquidated' immediately (combusted during bioenergy production and use) rather than decomposing slowly in the forest. Therefore, the associated change in forest carbon is the difference between immediate release (bioenergy) and decomposition over time if not collected. As noted previously, these factors could vary by location with a potentially significant impact on the assessed forest carbon emissions. We do not consider emissions related to the current harvest for traditional wood products or their use. Under the assumptions in this study, this is not affected by the decision to undertake additional harvest or collect residues for bioenergy production.

## Results and Discussion

**Life Cycle Inventory Results, Excluding Forest Carbon.** LCI results for the pathways are shown in Table 1, using the assumption of immediate biomass carbon neutrality. LCI emissions for biomass are greater when sourced from standing trees than from residues. Upstream (fuel production) stages, however, are minor contributors to LC emissions of either pellets or ethanol. The majority of emissions arise from the combustion of fossil fuels, both as the fossil portion during bioenergy use and in the reference fossil pathways. Excluding changes in forest carbon, 20% pellet cofiring reduces LC emissions by 18% compared to coal-only operation (kWh basis) whether standing trees or residues are utilized, whereas an E85-fueled LDV reduces LC emissions by 57% compared to a gasoline LDV (km-driven basis). The greater emission reduction of E85 relative to pellet cofiring gives the appear-

**TABLE 1. Life Cycle GHG Emissions Associated with Bioenergy Product (wood pellets, ethanol) Blended for Use and Substitution for Fossil Reference Pathway<sup>a</sup>**

life cycle stage	electricity generation pathways			transportation pathways		
	coal <sup>c,d</sup> (g CO <sub>2</sub> equiv/kWh)	20% pellet cofiring, residue (g CO <sub>2</sub> equiv/kWh)	20% pellet cofiring, standing tree <sup>e</sup> (g CO <sub>2</sub> equiv/kWh)	gasoline <sup>f</sup> (g CO <sub>2</sub> equiv/km)	E85, residue (g CO <sub>2</sub> equiv/km)	E85, standing tree (g CO <sub>2</sub> equiv/km)
forest operations		1.9	4.3		5.1	11.7
bioenergy production, distribution <sup>b</sup>		9.5	9.6		46	46
upstream fossil energy component	62	50	50	77	16	16
fuel use (combustion) <sup>e</sup>	939	760	760	211	48	48
total life cycle emissions	1001	821	824	288	116	123

<sup>a</sup> Values assume immediate carbon neutrality and do not take into consideration forest carbon implications. <sup>b</sup> Includes transport of biomass to the production facility, bioenergy production, electricity coproduct credit from biochemical production of ethanol, and bioenergy transportation/distribution stages. <sup>c</sup> Reference (6). <sup>d</sup> Surface coal mining removes biomass and disturbs soil, which results in GHG emissions due to direct land use change. These emissions along with other mining process emissions are considered in our analysis. <sup>e</sup> Fuel use consists of GHG emissions from the fossil component of fuel (coal, gasoline) and non-CO<sub>2</sub> GHG emissions associated with bioenergy (pellet, ethanol) combustion. <sup>f</sup> Reference (4).

**TABLE 2. Forest Carbon Impacts of Continuous Biomass Harvest**

biomass source	forest carbon stock change (MtCO <sub>2</sub> equiv)										
	year										
	0	10	20	30	40	50	60	70	80	90	100
residues	0 <sup>a,b</sup>	-8.2	-11.8	-13.0	-13.5	-13.9	-14.3	-14.7	-15.0	-15.2	-15.2
standing trees	0	-43.6	-80.9	-106.3	-112.5	-113.4	-112.7	-132.8	-143.6	-150.8	-150.7

<sup>a</sup> Negative values indicate a GHG emission source (forest carbon stocks are reduced due to biomass harvest) that is attributable to bioenergy production. <sup>b</sup> Reported values are the total stock change due to continuous harvest. For example, 50 years of continuous standing tree harvest reduces total forest carbon stocks by 113.4 MtCO<sub>2</sub>equiv.

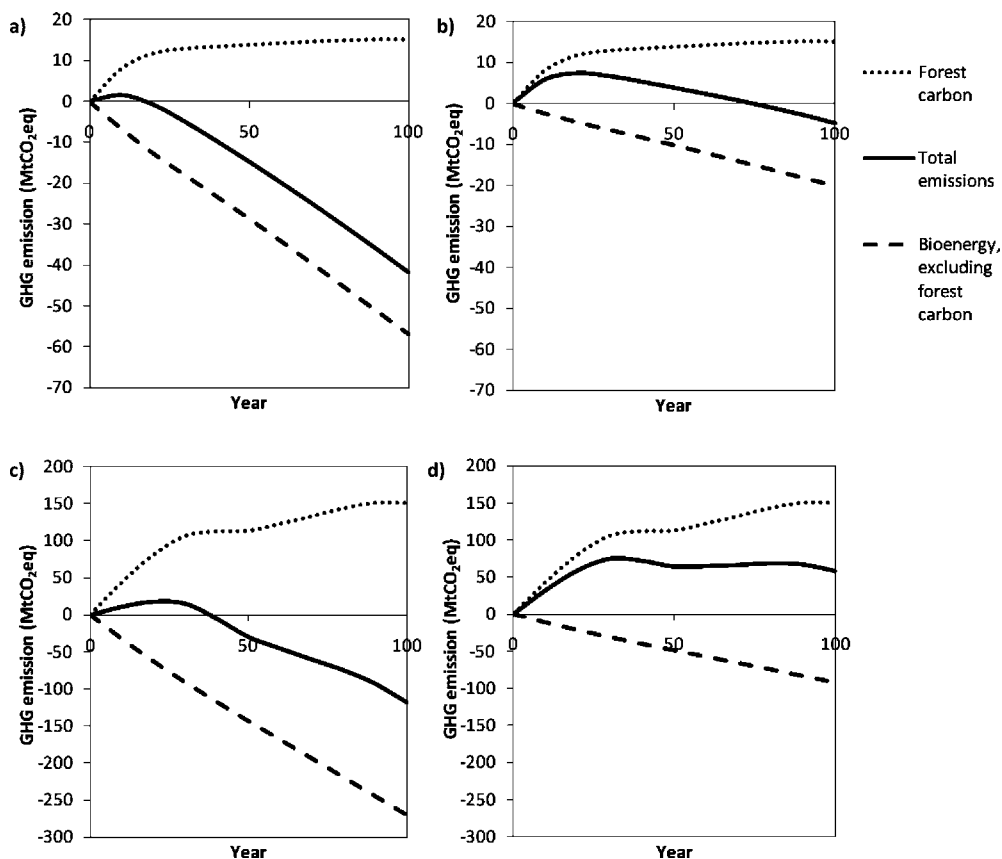
ance that this pathway represents a preferred use of biomass for reducing emissions, but this results primarily from the cofiring scenario utilizing a lower proportion of biomass fuel (20%, energy basis) than E85 (79%, energy basis).

We convert the LC emissions from their initial functional units (kWh, km driven) to a basis of one odt of biomass removed from the forest for bioenergy production (odt<sub>biomass</sub>). This makes the LCI and forest carbon model results compatible and facilitates a comparison of the two bioenergy pathways (electricity, ethanol) in terms of their effectiveness of biomass utilization in reducing emissions (see Supporting Information, equation S-3). Over their respective LCs, the production and use of pellets from standing trees displaces 1.49 tCO<sub>2</sub>equiv/odt<sub>biomass</sub>, while ethanol production and use displaces 0.51 tCO<sub>2</sub>equiv/odt<sub>biomass</sub>, exclusive of forest carbon impacts. Utilizing residues as a feedstock for pellets and ethanol displaces 1.50 and 0.53 tCO<sub>2</sub>equiv/odt<sub>biomass</sub>, respectively. Substitution of coal with pellets provides a greater mitigation benefit than substitution of gasoline with ethanol, primarily due to the higher GHG intensity of coal. To put these values into perspective, the constituent carbon in biomass is equivalent to 1.83 tCO<sub>2</sub>equiv/odt. The significance of releasing this biomass-based CO<sub>2</sub> is considered subsequently.

**Forest Carbon Analysis Results: Impact of Biomass Harvest.** Sustainable biomass sources in the study area could provide, on average, 1.8 million odt/year from standing trees and 0.38 million odt/year from residues. Combined, these sources could provide 2.2% of annual electricity generation in the province or reduce gasoline consumption by 3.3% (see Supporting Information). Forest carbon loss due to undertaking biomass harvest in the study area over a 100 year period is shown in Table 2. For both sources (residues, standing trees), harvest reduces forest carbon asymptotically toward a “steady state”. For standing trees, as more stands are harvested for bioenergy over time, the rate of carbon accumulation in regrowing stands increases toward a point where, under ideal conditions, carbon accumulation balances

removals associated with continued harvest. For residues, a similar steady state is eventually achieved when the rate of carbon removals at harvest is matched by the expected rate of residue decomposition if harvest is not undertaken. Continuing biomass harvest once a steady state has been reached would not impact forest carbon stocks; however, initiating biomass harvest beyond current removals has significant emissions consequences in the near to medium term. Forest carbon loss due to harvest residue collection approaches a maximum of ~15MtCO<sub>2</sub>equiv, whereas standing tree harvest for bioenergy results in a carbon loss exceeding 150 MtCO<sub>2</sub>equiv after 100 years. Proportional to the quantity of biomass provided, standing tree harvest results in a greater impact on forest carbon than harvest residue collection because live trees would generally continue to sequester carbon if not harvested, whereas carbon in uncollected residues declines over time.

**Total GHG Emissions: Combined LCI and Forest Carbon Analysis Results.** Summing the cumulative emissions of the bioenergy options (LCI results Figure 1, dashed lines) and the forest carbon emissions (Figure 1, dotted lines) results in the total emissions of bioenergy production and use (Figure 1, solid lines). When reductions in forest carbon are included, emission mitigation is delayed and reduced compared to the case where immediate biomass carbon neutrality is assumed. For all scenarios investigated, total emissions from the bioenergy pathways initially exceed those of the reference fossil fuel pathways, indicating an initial increase in emissions resulting from bioenergy use. Emissions associated with forest carbon loss due to biomass harvest exceed the reduction of fossil fuel-based emissions provided by bioenergy substitution. The emissions increase associated with bioenergy, however, is temporary: the rate of forest carbon loss decreases with time, whereas the emissions reduction associated with utilizing bioenergy in place of fossil alternatives continues to increase throughout the 100 year period, proportional to the cumulative quantity of pellets or ethanol produced. A



**FIGURE 1. Cumulative GHG emissions from continuous biomass harvest for bioenergy production: (a) pellets produced from residues, displacing coal (20% cofiring), (b) ethanol produced from residues, displacing gasoline (E85 fuel), (c) pellets produced from standing trees, displacing coal (20% cofiring), and (d) ethanol produced from standing trees, displacing gasoline (E85 fuel). Positive values indicate an increase in GHG emissions to the atmosphere.**

time delay therefore exists before bioenergy systems reach a “break-even” point where total emissions for the bioenergy and reference fossil pathways are equal. Only after the break-even point are net emissions reductions achieved.

Figure 1a and 1b shows the total emissions resulting from continuous use of residues for pellet and ethanol production, respectively, over a 100 year period. Excluding forest carbon, the emissions reduction associated with utilizing bioenergy in place of fossil alternatives increases steadily over time. The reduction of forest carbon stocks due to residue collection slows toward a steady state. Co-firing with pellets produced from residues reduces cumulative emissions relative to coal only after an initial period of increased emissions lasting 16 years. Forest carbon impacts of residue removal reduce the total emission mitigation at year 100 from 57 MtCO<sub>2</sub>equiv (expected assuming immediate biomass carbon neutrality) to 42 MtCO<sub>2</sub>equiv.

Compared to the electricity pathway results, utilization of residues for ethanol production is more greatly impacted by changes in forest carbon, due to the lower GHG intensity of the displaced fuel (gasoline compared to coal). An overall emission reduction occurs only after 74 years of continuous production of ethanol; total GHG reductions by year 100 are reduced by 76% from expected performance assuming immediate biomass carbon neutrality.

Due to the greater forest carbon impact of standing tree harvest compared to residue collection, bioenergy production from standing trees performs worse in terms of reducing emissions (Figure 1c and 1d). Pellet production from standing trees results in a greater initial emissions increase, reaching a break-even point only after 38 years of continuous production and use when displacing coal for electricity generation. The total emissions reductions from utilizing

wood pellets from standing trees over a 100 year period, expected under the assumption of biomass carbon neutrality, is reduced by 56% when forest carbon impacts are considered.

As in the residue cases, for the standing tree cases forest carbon more significantly impacts total emissions of ethanol than those associated with pellets for electricity generation. Ethanol production from standing trees (Figure 1d) does not reduce emissions at any point within the 100 year period; instead, overall emissions to the atmosphere increase relative to the gasoline reference pathway. Disregarding biobased CO<sub>2</sub> emissions, as is common to most LCAs, would return an opposite, and erroneous, result. This contradiction, also identified elsewhere (15), illustrates the misleading consequence of assuming immediate biomass carbon neutrality when quantifying emissions of some bioenergy pathways.

Simply adding biobased CO<sub>2</sub> emissions associated with bioenergy production and use to the LCI totals presented in Table 1 would increase emissions associated with bioenergy. Pellet cofiring (at 20%) would result in (all in gCO<sub>2</sub>equiv/kWh) 1039 (residue) and 1042 (standing tree) compared to 1001 for coal only. E85 would emit (all in gCO<sub>2</sub>equiv/km) 711 (residue) and 718 (standing tree) compared to 288 for gasoline. This approach, however, would not accurately assess the impact of bioenergy production and use on the atmosphere. By only considering carbon in harvested biomass, near-term emissions would be underestimated (decomposition of uncollected biomass, for example, below ground biomass, is omitted). Mid- to long-term emissions would be overestimated as compensation for biobased CO<sub>2</sub> emissions within the forest (e.g., regrowth) is not considered.

**Sensitivity Analysis.** A sensitivity analysis is performed to assess the impact of key sources of uncertainty/variability in the LCI and forest carbon model parameters on the study

results (see Supporting Information). The results are not sensitive to most parameters, and the general trends of the impacts of biomass harvest on carbon stocks and their contribution to overall emissions were not found to be impacted by uncertainty in the parameters. The pellet pathway results were found to be most sensitive to assumptions related to the quantity of biomass used for drying during pelletization (15% of input biomass in base case) (see Supporting Information Figure S-3). Reducing the consumption of biomass during the drying stage increases pellet output and fossil fuel displacement per unit of input biomass. Collocation of pelletization facilities with processes generating waste heat could reduce the drying energy requirement. If no input biomass is required for drying, there are larger emissions reductions associated with pellet use and the time before reaching break even with the fossil energy system is reduced from 16 to 11 years (residues) and from 38 to 29 years (standing trees). When forest carbon is excluded from the analysis, biomass utilization for drying energy has a minimal impact on LC emissions (6).

**Study Implications.** The simplified assumption of immediate biomass carbon neutrality has been commonly employed in bioenergy studies, owing in part to emissions from the energy and forest sectors being reported separately in national inventories (17). This study, however, shows that increasing biomass removals from the forest significantly reduces carbon stocks and delays and lessens the GHG mitigation potential of the bioenergy pathways studied. Ignoring the complex relationship between forest carbon stocks and biomass harvest by employing the carbon neutrality assumption overstates the GHG mitigation performance of forest bioenergy and fails to report delays in achieving overall emissions reductions.

Combining LCI analysis and forest carbon modeling as an analytical approach provides a more accurate representation of the role of forest bioenergy in GHG mitigation. When forest carbon dynamics are included in the case study, the use of forest-based bioenergy increases overall emissions for many years and, in the worst-performing scenario (standing tree harvest for ethanol production), does not yield any net climate mitigation benefit over the 100 year period. Carbon implications of bioenergy production are not limited to forests, and these results should not be taken to suggest that agricultural biomass is inherently preferable. Land use impacts associated with agriculture-sourced bioenergy can greatly increase LC emissions (7). Nonbioenergy systems can also impact carbon stocks (e.g., overburden removal in coal mining). While the contribution to total emissions may not be significant in all situations, a comprehensive evaluation of any fossil or renewable system should consider impacts of life cycle activities on terrestrial carbon stocks.

Do our results support continued reliance on fossil fuels for electricity generation and transportation? Fossil fuel use transfers carbon from the Earth's crust to the atmosphere; moving beyond reliance on these energy sources is imperative to address climate change and nonrenewable resource concerns. Bioenergy offers advantages over other renewable options that are limited by supply intermittency and/or high cost. However, effective deployment of bioenergy requires the thoughtful selection of appropriate pathways to achieve overall emissions reductions. Harvesting standing trees for structural wood products has been reported to reduce overall emissions: storing carbon in wood products and displacing GHG-intensive materials (steel, concrete) exceeds associated forest carbon impacts (14). In comparison, using standing trees for bioenergy immediately transfers carbon to the atmosphere and provides a relatively smaller GHG benefit from displacing coal or gasoline, increasing overall emissions for several decades. Identifying biomass supply scenarios that minimize forest carbon loss will improve the emission

mitigation performance of forest bioenergy. Residues employed for bioenergy reduce emissions from coal after a much smaller delay than standing trees, while other forest biomass sources (e.g., processing residuals) could offer near-term emission reductions if used to replace GHG-intensive fossil fuels. Industrial ecology approaches (e.g., utilizing end-of-life wood products as a biomass source; integrating bioenergy production with other wood products to utilize waste heat for processing) could reduce forest carbon implications of bioenergy production and are deserving of further consideration.

Utilizing bioenergy to displace the most GHG-intensive fossil fuels minimizes initial emissions increases and reduces the time required before net GHG benefits are achieved. Ethanol production for gasoline displacement, under the modeled conditions, is not an effective use of forest biomass for GHG reductions. Displacing coal in electricity generation, in comparison, is superior in reducing emissions. However, this does not indicate that electricity applications are always preferable. The mitigation performance of biomass-derived electricity depends on the displaced generation source. Further, these results represent the expected near-term state of energy system technologies and do not consider changes in either the reference or the bioenergy pathways over the time frame studied. Performance improvements are inevitable with technological maturation and commercialization. Technological developments regarding thermal electricity generation (e.g., efficiency improvements; viable carbon capture and storage) would be applicable to both biomass and coal, while improvements in pellet production would not greatly influence total emissions. Emissions from producing ethanol, regarding both the ethanol production process and the appropriate reference pathway in the future given the limited petroleum supply and associated price volatility, is uncertain and in the future could prove a more effective means of emissions reductions than reported here. Ethanol can also play an important role in addressing economic and energy security concerns related to petroleum dependency.

Although the method demonstrated in this research is generalizable, site-specific characteristics of forests prevent the generalization of specific results from this study. Numerous factors would influence forest carbon dynamics and must be considered in specific analyses. Intensifying silvicultural practices (e.g., planting instead of natural regeneration, utilization of fast-growing species) could shorten, but not eliminate, the period of net emission increase found in our results. In some jurisdictions, residues are burned during site preparation for forest regrowth. Using such residues for bioenergy would not significantly impact forest carbon stocks.

While GHG mitigation is an important consideration of forest resource utilization, numerous other factors must be considered in the decision-making process. In particular, declines in Ontario's forest sector have negatively impacted communities that would welcome the investment and employment opportunities associated with bioenergy. Other environmental factors and technical constraints must be considered before implementing bioenergy production.

The potential of forest-based bioenergy to reduce emissions from fossil fuels must be balanced with forest carbon impacts of biomass procurement. This perspective is of particular importance as policies related to climate change mitigation, deployment of renewable energy, and the forest bioeconomy are developed and implemented. Considering bioenergy in isolation of its impact on forest carbon could inadvertently encourage the transfer of emissions from the energy sector to the forest sector rather than achieve real reductions. Accounting methods must be designed to measure the complete impact of mitigation options on the atmosphere. By considering the broader impacts of bioenergy production on the forest, particularly forest carbon pools,



policy can lend support to effective uses of forest resources for climate change mitigation.

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### Supporting Information Available

Additional detail on biomass sources, life cycle inventory of bioenergy systems, forest carbon analysis, and additional results and discussion. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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complement prior studies that highlight the importance of short- and medium-lived pollutants (14–17).

The top 10 pollutant-generating activities contributing to net RF (positive RF minus negative RF) in year 20 are shown in the bottom chart, page 526, which takes into account the emission of multiple pollutants from each source activity (18). The seven sources that appear only on the left side (purple bars) would be overlooked by mitigation strategies focusing exclusively on long-lived pollutants.

The distinctly different sources of near-term and long-term RF lend themselves to the aforementioned two-pronged mitigation approach. This decoupling is convenient for policy design and implementation; whereas the importance of long-term climate stabilization is clear, the perceived urgency of near-term mitigation will evolve with our knowledge of the climate system. Additionally, optimal near-term mitigation strategies will reflect decadal oscillations (19), seasonal and regional variations (20, 21), and evolving knowledge of aerosol-climate effects (22, 23) and methane-atmosphere interactions (22)—considerations unique to the near term.

Thus, short- and medium-lived sources (black carbon, tropospheric ozone, and methane) must be regulated separately and dynamically. The long-term mitigation treaty should focus exclusively on steady reduction of long-lived pollutants. A separate treaty for short- and medium-lived sources should include standards that evolve based on periodic recommendations of an independent international scientific panel. The framework of “best available control technology” (strict) and “lowest achievable emissions rate” (stricter) from the U.S. Clean Air Act (24) can be used as a model.

Such a two-pronged institutional framework would reflect the evolving scientific understanding of near-term climate change, the scientific certainty around long-term climate change, and the opportunity to separately adjust the pace of near-term and long-term mitigation efforts.

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#### Supporting Online Material

[www.sciencemag.org/cgi/content/full/326/5952/526/DC1](http://www.sciencemag.org/cgi/content/full/326/5952/526/DC1)

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## CLIMATE CHANGE

# Fixing a Critical Climate Accounting Error

Timothy D. Searchinger,<sup>1\*</sup> Steven P. Hamburg,<sup>2\*</sup> Jerry Melillo,<sup>3</sup> William Chameides,<sup>4</sup> Petr Havlik,<sup>5</sup> Daniel M. Kammen,<sup>6</sup> Gene E. Likens,<sup>7</sup> Ruben N. Lubowski,<sup>2</sup> Michael Obersteiner,<sup>5</sup> Michael Oppenheimer,<sup>1</sup> G. Philip Robertson,<sup>8</sup> William H. Schlesinger,<sup>7</sup> G. David Tilman<sup>9</sup>

Rules for applying the Kyoto Protocol and national cap-and-trade laws contain a major, but fixable, carbon accounting flaw in assessing bioenergy.

The accounting now used for assessing compliance with carbon limits in the Kyoto Protocol and in climate legislation contains a far-reaching but fixable flaw that will severely undermine greenhouse gas reduction goals (1). It does not count CO<sub>2</sub> emitted from tailpipes and smokestacks when bioenergy is being used, but it also does

not count changes in emissions from land use when biomass for energy is harvested or grown. This accounting erroneously treats all bioenergy as carbon neutral regardless of the source of the biomass, which may cause large differences in net emissions. For example, the clearing of long-established forests to burn wood or to grow energy crops is counted as a 100% reduction in energy emissions despite causing large releases of carbon.

Several recent studies estimate that this error, applied globally, would create strong incentives to clear land as carbon caps tighten. One study (2) estimated that a global CO<sub>2</sub> target of 450 ppm under this accounting would cause bioenergy crops to expand to displace virtually all the world’s natural forests and savannahs by 2065, releasing up to 37 gigatons (Gt) of CO<sub>2</sub> per year (compa-

<sup>1</sup>Princeton University, Princeton, NJ 08544, USA. <sup>2</sup>Environmental Defense Fund, Boston, MA 02108, and Washington, DC 20009, USA. <sup>3</sup>Marine Biological Laboratory, Woods Hole, MA 02543, USA. <sup>4</sup>Duke University, Durham, NC 27708, USA. <sup>5</sup>International Institute for Applied Systems Analysis, Laxenburg 2361, Austria. <sup>6</sup>University of California at Berkeley, Berkeley, CA 94720, USA. <sup>7</sup>Cary Institute of Ecosystem Studies, Millbrook, NY 12545, USA. <sup>8</sup>Michigan State University, Hickory Corners, MI 49060, USA. <sup>9</sup>University of Minnesota, St. Paul, MN 55108, USA.

\*Authors for correspondence. E-mail: [shamburg@edf.org](mailto:shamburg@edf.org) (S.P.H.); [tsearchi@princeton.edu](mailto:tsearchi@princeton.edu) (T.D.S.).

erable to total human CO<sub>2</sub> emissions today). Another study predicts that, based solely on economic considerations, bioenergy could displace 59% of the world's natural forest cover and release an additional 9 Gt of CO<sub>2</sub> per year to achieve a 50% "cut" in greenhouse gases by 2050 (3). The reason: When bioenergy from any biomass is counted as carbon neutral, economics favor large-scale land conversion for bioenergy regardless of the actual net emissions (4).

The potential of bioenergy to reduce greenhouse gas emissions inherently depends on the source of the biomass and its net land-use effects. Replacing fossil fuels with bioenergy does not by itself reduce carbon emissions, because the CO<sub>2</sub> released by tailpipes and smokestacks is roughly the same per unit of energy regardless of the source (1, 5). Emissions from producing and/or refining biofuels also typically exceed those for petroleum (1, 6). Bioenergy therefore reduces greenhouse emissions only if the growth and harvesting of the biomass for energy captures carbon above and beyond what would be sequestered anyway and thereby offsets emissions from energy use. This additional carbon may result from land management changes that increase plant uptake or from the use of biomass that would otherwise decompose rapidly. Assessing such carbon gains requires the same accounting principles used to assign credits for other land-based carbon offsets.

For example, if unproductive land supports fast-growing grasses for bioenergy, or if forestry improvements increase tree growth rates, the additional carbon absorbed offsets emissions when burned for energy. Energy use of manure or crop and timber residues may also capture "additional" carbon. However, harvesting existing forests for electricity adds net carbon to the air. That remains true even if limited harvest rates leave the carbon stocks of regrowing forests unchanged, because those stocks would otherwise increase and contribute to the terrestrial carbon sink (1). If bioenergy crops displace forest or grassland, the carbon released from soils and vegetation, plus lost future sequestration, generates carbon debt, which counts against the carbon the crops absorb (7, 8).

The Intergovernmental Panel on Climate Change (IPCC) has long realized that bioenergy's greenhouse effects vary by source of biomass and land-use effects. It also recognizes that when forests or other plants are harvested for bioenergy, the resulting carbon release must be counted either as land-use emissions or energy emissions but not both.

To avoid double-counting, the IPCC assigns the CO<sub>2</sub> to the land-use accounts and exempts bioenergy emissions from energy accounts (5). Yet it warns, because "fossil fuel substitution is already 'rewarded'" by this exemption, "to avoid underreporting . . . any changes in biomass stocks on lands . . . resulting from the production of biofuels would need to be included in the accounts" (9).

This symmetrical approach works for the reporting under the United Nations Framework Convention on Climate Change (UNFCCC) because virtually all countries report emissions from both land and energy use. For example, if forests are cleared in Southeast Asia to produce palm biodiesel burned in Europe, Europe can exclude the tailpipe emissions as Asia reports the large net carbon release as land-use emissions.

However, exempting emissions from bioenergy use is improper for greenhouse gas regulations if land-use emissions are not included. The Kyoto Protocol caps the energy emissions of developed countries. But the protocol applies no limits to land use or any other emissions from developing countries, and special crediting rules for "forest management" allow developed countries to cancel out their own land-use emissions as well (1, 10). Thus, maintaining the exemption for CO<sub>2</sub> emitted by bioenergy use under the protocol (11) wrongly treats bioenergy from all biomass sources as carbon neutral, even if the source involves clearing forests for electricity in Europe or converting them to biodiesel crops in Asia.

This accounting error has carried over into the European Union's cap-and-trade law and the climate bill passed by the U.S. House of Representatives (1, 12, 13). Both regulate emissions from energy but not land use and then erroneously exempt CO<sub>2</sub> emitted from bioenergy use. In theory, the accounting system would work if caps covered all land-use emissions and sinks. However, this approach is both technically and politically challenging as it is extremely hard to measure all land-use emissions or to distinguish human and natural causes of many emissions (e.g., fires).

The straightforward solution is to fix the accounting of bioenergy. That means tracing the actual flows of carbon and counting emissions from tailpipes and smokestacks whether from fossil energy or bioenergy. Instead of an assumption that all biomass offsets energy emissions, biomass should receive credit to the extent that its use results in additional carbon from enhanced plant growth or from the use of residues or biowastes. Under any crediting system, credits must reflect net changes in carbon stocks, emissions of non-CO<sub>2</sub> greenhouse gases, and leakage emissions resulting from

changes in land-use activities to replace crops or timber diverted to bioenergy (1).

Separately, Europe and the United States have established legal requirements for minimum use of biofuels, which assess greenhouse gas consequences based on life-cycle analyses that reflect some land-use effects (1, 14). Such assessments vary widely in comprehensiveness, but none considers biofuels free from land-based emissions. Yet the carbon cap accounting ignores land-use emissions altogether, creating its own large, perverse incentives.

Bioenergy can provide much energy and help meet greenhouse caps, but correct accounting must provide the right incentives.

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#### Supporting Online Material

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# Frontiers in Ecology and the Environment

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## Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions?

John L Campbell, Mark E Harmon, and Stephen R Mitchell

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# Can fuel-reduction treatments really increase forest carbon storage in the western US by reducing future fire emissions?

John L Campbell<sup>1\*</sup>, Mark E Harmon<sup>1</sup>, and Stephen R Mitchell<sup>2</sup>

It has been suggested that thinning trees and other fuel-reduction practices aimed at reducing the probability of high-severity forest fire are consistent with efforts to keep carbon (C) sequestered in terrestrial pools, and that such practices should therefore be rewarded rather than penalized in C-accounting schemes. By evaluating how fuel treatments, wildfire, and their interactions affect forest C stocks across a wide range of spatial and temporal scales, we conclude that this is extremely unlikely. Our review reveals high C losses associated with fuel treatment, only modest differences in the combustive losses associated with high-severity fire and the low-severity fire that fuel treatment is meant to encourage, and a low likelihood that treated forests will be exposed to fire. Although fuel-reduction treatments may be necessary to restore historical functionality to fire-suppressed ecosystems, we found little credible evidence that such efforts have the added benefit of increasing terrestrial C stocks.

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Various levels of tree removal, often paired with prescribed burning, are a management tool commonly used in fire-prone forests to reduce fuel quantity, fuel continuity, and the associated risk of high-severity forest fire. Collectively referred to as “fuel-reduction treatments”, such practices are increasingly used across semi-arid forests of the western US, where a century of fire suppression has allowed fuels to accumulate to levels deemed unacceptably hazardous. The efficacy of fuel-reduction treatments in temporarily reducing fire hazard in forests is generally accepted (Agee and Skinner 2005; Ager *et al.* 2007; Stephens *et al.* 2009a) and, depending on the prescription, may serve additional management objectives, including the restoration of native species composition, protection from insect and pathogen outbreaks, and provision of wood products and associated employment opportunities.

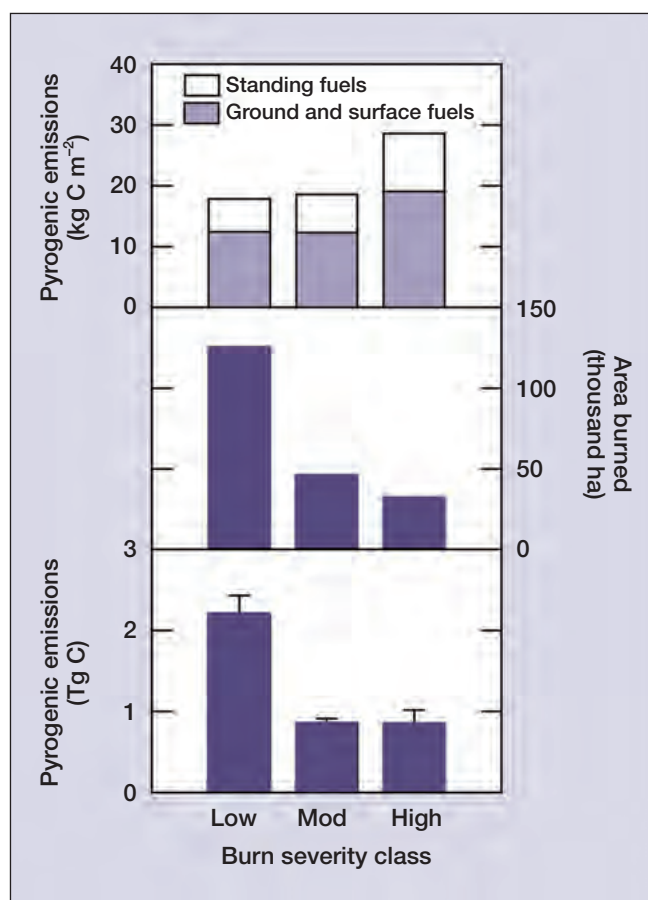
## In a nutshell:

- Carbon (C) losses incurred with fuel removal generally exceed what is protected from combustion should the treated area burn
- Even among fire-prone forests, one must treat about ten locations to influence future fire behavior in a single location
- Over multiple fire cycles, forests that burn less often store more C than forests that burn more often
- Only when treatments change the equilibrium between growth and mortality can they alter long-term C storage

Recently, several authors have suggested that fuel-reduction treatments are also consistent with efforts to sequester C in forest biomass, thus reducing atmospheric carbon dioxide (CO<sub>2</sub>) levels (Frinkral and Evans 2008; Hurteau *et al.* 2008; Hurteau and North 2009; Stephens *et al.* 2009b). It is argued that short-term losses in forest biomass associated with fuel-reduction treatments are more than made up for by the reduction of future wildfire emissions, and thinning practices aimed at reducing the probability of high-severity fire should therefore be given incentives rather than be penalized in C-accounting programs. This is an appealing notion that aligns the practice of forest thinning with four of the most pressing environmental and societal concerns facing forest managers in this region today – namely, fire hazard, economic stimulus, so-called forest health, and climate-change mitigation. However, we believe that current claims that fuel-reduction treatments function to increase forest C sequestration are based on specific and sometimes unrealistic assumptions regarding treatment efficacy, wildfire emissions, and wildfire burn probability.

In this paper, we combine empirical data from various fire-prone, semiarid conifer forests of the western US (where issues of wildfire and fuel management are most relevant) with basic principles of forest growth, mortality, decomposition, and combustion. Our goal is to provide a complete picture of how fuel treatments and wildfires affect aboveground forest C stocks by examining these disturbance events (1) for a single forest patch, (2) across an entire forest landscape, (3) after a single disturbance, and (4) over multiple disturbances. Finally, we consider how wildfire and/or fuel treatments could initiate alternate equilibrium states

<sup>1</sup>Department of Forest Ecosystems and Society, Oregon State University, Corvallis, OR \*(john.campbell@oregonstate.edu); <sup>2</sup>Nicholas School of the Environment, Duke University, Durham, NC



**Figure 1.** Sources of pyrogenic emissions across the 2002 Biscuit Fire in southwestern Oregon and northern California. Because most emissions arise from the combustion of ground and surface fuels, pyrogenic emissions from high-severity fires were only one-third higher than those in low-severity fires. Moreover, because most of the fire burned with low severity, the contribution of high-severity fire to total emissions was only about 20%. The Biscuit Fire burned over a mosaic of young, mature, and old-growth stands of mixed conifer growing across a climate gradient ranging from mesic to semiarid. Methods are described in Campbell *et al.* (2007).

and change the long-term capacity of a forest to accumulate biomass.

#### ■ Immediate stand-level C losses attributed to wildfire and fuel-reduction treatments

Because fuel-reduction treatments are generally designed to reduce subsequent wildfire severity, rather than to preclude fire entirely, it is important to compare the C losses incurred under both high- and low-severity fire scenarios. The amount of biomass combusted in a high-severity crown fire is unquestionably greater than the amount combusted in a low-severity surface fire. The difference, however, is smaller than that suggested by some authors (eg Hurteau *et al.* 2008). Even under the most extreme fuel-moisture conditions, the water content of live wood frequently prohibits combustion beyond surface char; this

is evident in the retention of even the smallest canopy branches after high-severity burns (Campbell *et al.* 2007). Moreover, the consumption of fine surface fuels (ie leaf litter, fallen branches, and understory vegetation), though variable, can be high even in low-severity burns. As shown in Figure 1, Campbell *et al.* (2007) found that patches of mature mixed-conifer forest in southwestern Oregon that were subject to low-severity fire (ie 0–10% overstory mortality) released 70% as much C per unit area as did locations experiencing high-severity fire (ie > 80% overstory mortality). When scaled over an entire wildfire perimeter, the importance of high-severity fire in driving pyrogenic emissions is further diminished because crown fires are generally patchy while surface fires are nearly ubiquitous (Meigs *et al.* 2009).

According to Campbell *et al.* (2007), less than 20% of the estimated 3.8 teragrams of C released to the atmosphere by the 2002 Biscuit Fire in the Siskiyou National Forest of southern Oregon and northern California (Figure 1) arose from overstory combustion. Simply put, because most pyrogenic emissions arise from the combustion of surface fuels, and most of the area within a typical wildfire experiences surface-fuel combustion, efforts to minimize overstory fire mortality and subsequent necromass decay are limited in their ability to reduce fire-wide pyrogenic emissions.

The total amount of biomass combusted, or taken off-site, during a fuel treatment is, by definition, a prescribed quantity and can vary widely depending on the specific management objective and techniques used. A review of fuel-reduction treatments carried out in semiarid conifer forests in the western US reveals that aboveground C losses associated with treatment averaged approximately 10%, 30%, and 50% for prescribed fire only, thinning only, and thinning followed by prescribed fire, respectively (WebTable 1). By comparison, wildfires burning over comparable fire-suppressed forests consume an average 12–22% of the aboveground C (total fire-wide averages reported by Campbell *et al.* [2007] and Meigs *et al.* [2009], respectively).

Given that both fuel-reduction treatments and wildfire remove C from a forest, to what degree does the former reduce the impact of the latter? To test this question, Mitchell *et al.* (2009) simulated wildfire combustion following a wide range of fuel-reduction treatments for three climatically distinct conifer forest types in Oregon. As illustrated in Figure 2, fuel treatments were effective in reducing combustion in a subsequent wildfire, and the greater the treatment intensity, the greater the reduction in future combustion. However, even in the mature, fire-suppressed ponderosa pine (*Pinus ponderosa*) forest, protecting one unit of C from wildfire combustion typically came at the cost of removing three units of C in treatment. The reason for this is simple: the efficacy of fuel-reduction treatments in reducing future wildfire emissions comes in large part by removing or combusting surface fuels ahead of time. Furthermore, because remov-

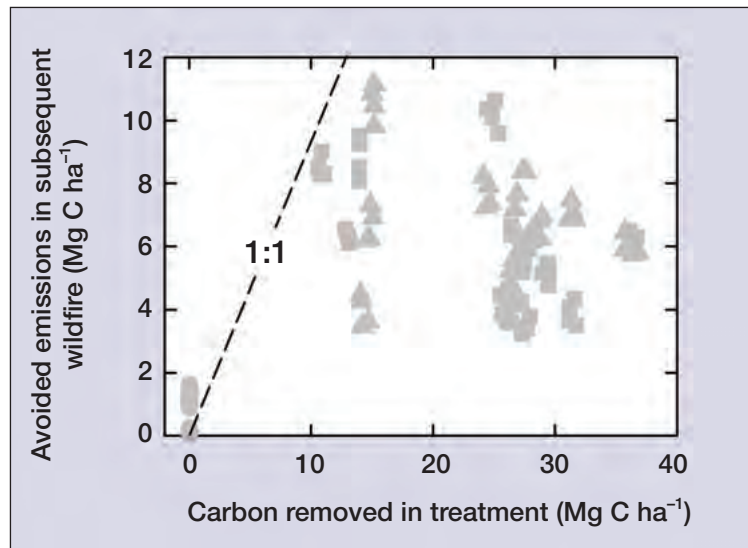
ing fine canopy fuels (ie leaves and twigs) practically necessitates removing the branches and boles to which they are attached, conventional fuel-reduction treatments usually remove more C from a forest stand than would a wildfire burning in an untreated stand. In an extreme modeling scenario, wherein only fine-surface fuels were removed, subsequent avoided combustion did slightly exceed treatment removals (Figure 2, circles). However, this marginal gain amounted to less than 0.03% of the total C stores, which is, practically speaking, a zero-sum game.

#### ■ Wildfire probability, treatment life span, and treatment efficacy across a landscape

Any approach to C accounting that assumes a wildfire burn probability of 100% during the effective life span of a fuel-reduction treatment is almost certain to overestimate the ability of such treatments to reduce pyrogenic emissions on the future landscape. Inevitably, some fraction of the land area from which biomass is thinned will not be exposed to any fire during the treatment's effective life span and therefore will incur no benefits of reduced combustion (Rhodes and Baker 2008). On the other hand, assuming that landscape-wide burn probabilities apply to all of the treated area is almost certain to underestimate the influence of treatment on future landscape combustion. This is because doing so does not account for managers' ability to target treatments toward probable ignition sources or the capacity of treated areas to reduce burn probability in adjacent untreated areas (Ager *et al.* 2010).

Among fire-prone forests of the western US, the combination of wildfire starts and suppression efforts result in current burn probabilities of less than 1% (WebTable 2). Given a fuel-treatment life expectancy of 10–25 years, only 1–20% of treated areas will ever have the opportunity to affect fire behavior. Such approximations are consistent with a similar analysis reported by Rhodes and Baker (2008), who suggested that only 3% of the area treated for fuels is likely to be exposed to fire during their assumed effective life span of 20 years. Extending treatment efficacy by repeated burning of understory fuels could considerably increase the likelihood of a treated stand to affect wildfire behavior, but such efforts come at the cost of more frequent C loss.

A more robust, though more complicated, evaluation of fuel-treatment effect on landscape burn probability is achieved through large-scale, spatially explicit fire spread simulations (Miller 2003; Syphard *et al.* 2011). In one such simulation, representing both the topography and distribution of fuels across a fire-prone and fire-suppressed landscape in western Montana, Finney *et al.* (2007) showed how strategically treating as little as 1% of the



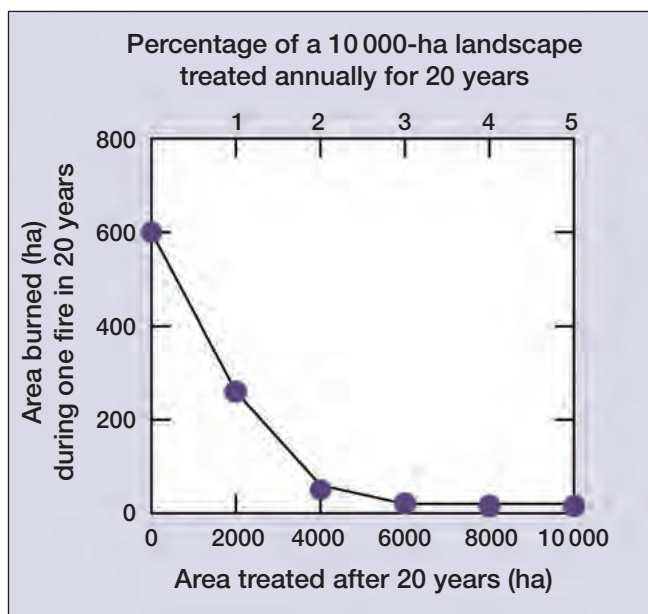
**Figure 2.** Simulated effectiveness of various fuel-reduction treatments in reducing future wildfire combustion in a ponderosa pine (*Pinus ponderosa*) forest. In general, protecting one unit of C from wildfire combustion came at the cost of removing approximately three units of C in treatment. At the very lowest treatment levels, more C was protected from combustion than removed in treatment; however, the absolute gains were extremely low. Circles show understory removal, squares show prescribed fire, and triangles show understory removal and prescribed fire. Simulations were run for 800 years with a treatment-return interval of 10 years and a mean fire-return interval of 16 years. Forest structure and growth were modeled to represent mature, semiarid ponderosa pine forest growing in Deschutes, Oregon. Further descriptions of these simulations are given in Mitchell *et al.* (2009).

forest annually for 20 years reduced the area impacted by a single large wildfire (expected to occur about once on this landscape in that 20-year period) by half, and how strategically treating 4% of the forest annually reduced the area impacted by a single large wildfire by >95% (Figure 3). However, even when the treatment effect was highest, the protection of each hectare of forest from fire came at the cost of treating nearly 10 hectares (note the axis scales in Figure 3). Such inefficiencies come not from the treatments' efficacy in curtailing fire spread; rather, they stem from the rarity of wildfire. Put another way, the treatment of even modest areas may lead to high fractional reductions in the area impacted by high-severity wildfire, but because such fires rarely affect much of the landscape, the absolute change in area burned is small.

#### ■ Carbon dynamics through an entire disturbance cycle

Although there is a body of literature that separately quantifies the decomposition of standing dead trees, dead tree fall rate, and the decomposition of downed woody debris, there are surprisingly few empirical studies that integrate these processes to estimate the overall longevity of fire-killed trees. Combining disparate estimates of standing and downed wood decay with tree-fall rates sug-





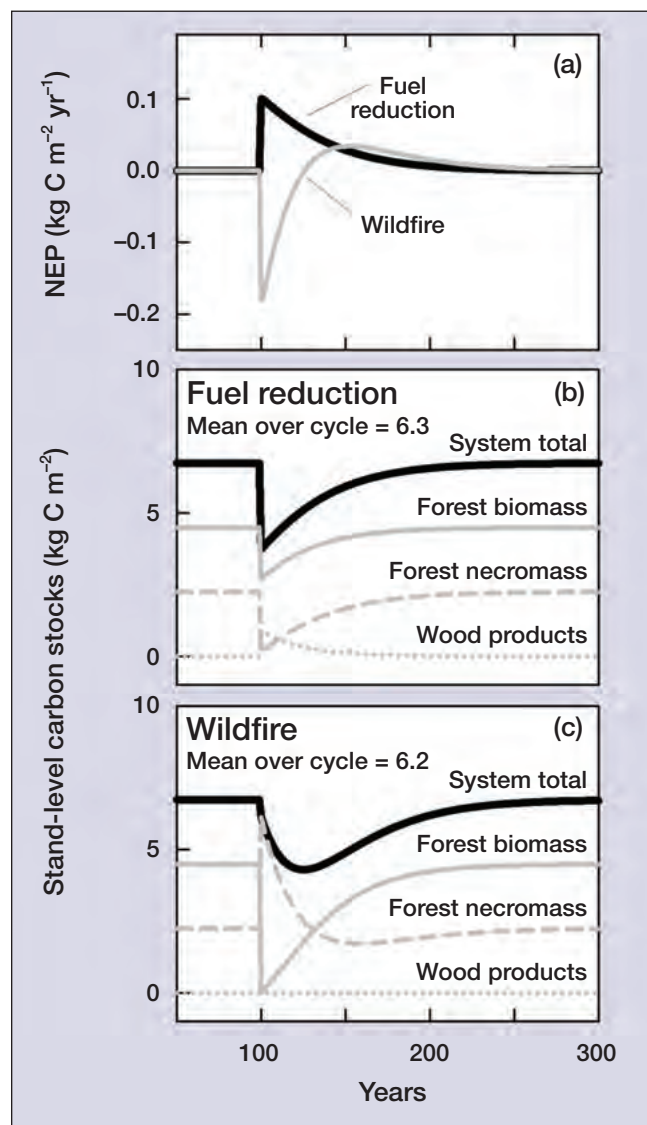
**Figure 3.** Simulated effects of strategically placed fuel treatments on wildfire spread across a fire-prone ponderosa and lodgepole pine (*Pinus contorta*) landscape in western Montana. Treating only 1% of the forest annually for 20 years reduced the area impacted by a single large wildfire (assumed to occur about once in 20 years) by more than half. However, across this entire treatment response, the protection of one hectare of forest from fire required the treatment of about 10 hectares. Adapted from Finney *et al.* (2007).

gests that the overall rate at which fire-killed trees decompose in a semiarid conifer forest likely ranges between 1–9% annually (ie a half-life of 8–70 years). These values are consistent with the observations of Donato (unpublished data), who found that 52% of the biomass killed in a forest-replacing wildfire in southwestern Oregon was still present after 18 years.

It is reasonable to expect that in the first decade or two after a forest-replacing fire, the decomposition of fire-killed trees may exceed the net primary production (NPP) of re-establishing vegetation, thus driving net ecosystem production (NEP) below zero. This expectation is supported by eddy covariance flux measurements (Dore *et al.* 2008) and other empirical studies of post-fire vegetation (Irvine *et al.* 2007; Meigs *et al.* 2009). However, despite a protracted period of negative NEP fol-

**Figure 4.** (a) Simulated net ecosystem production and (b–c) C stocks throughout an entire disturbance interval, initiated by either wildfire or fuel-reduction treatment. Unlike the stand subject to fuel reduction via thinning, the combination of low biomass and high necromass after wildfire functions to drive NEP below zero. Nevertheless, although initial losses associated with wildfire were much lower than those in the fuel-reduction treatment, the two scenarios achieved parity in C stocks over the entire disturbance interval. The model used to generate these simulations was parameterized for a ponderosa pine forest representative of the eastern Cascades and is fully described in WebFigure 1.

lowing a fire event, total C stocks integrated over the entire disturbance cycle may be similar for a forest subject to a fuel-reduction treatment and one subject to a stand-replacing fire. This can easily be shown with a simple C model that simulates growth, mortality, decomposition, and combustion for ponderosa pine forests (Figure 4). How can this be? Simply put, biomass recovery may be slower in the wildfire scenario than in the fuel-reduction scenario, but initial biomass losses may be greater in the fuel-reduction scenario than in the wildfire scenario. Although the parameters used to generate Figure 4 (ie 30% live basal-area removal in the treatment scenario, 100% tree mortality in the wildfire scenario, and rapid post-fire regeneration) are reasonable, real-world responses may not exhibit such parity in integrated C stocks between disturbance types. The point of this simulation is to demonstrate how marked differences in post-disturbance NEP do not necessarily translate into differences in C stocks integrated over time. The quantification of NEP over short intervals is extremely valuable in teasing apart ecosystem C dynamics; however,

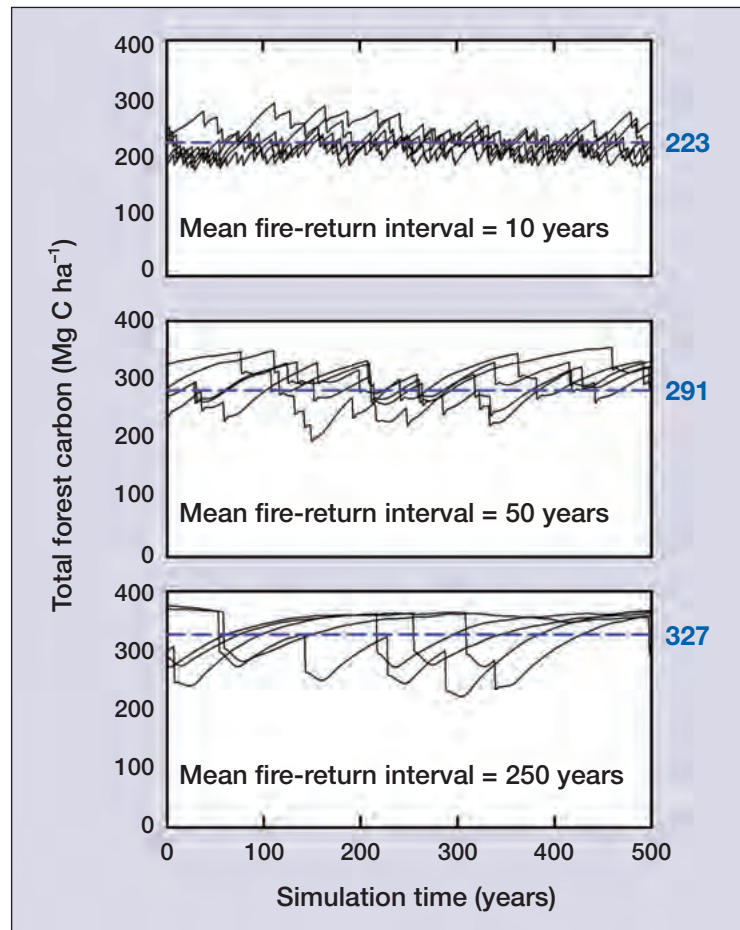


simply comparing C flux rates immediately following different disturbances can give a misleading picture of how disturbances dictate long-term C balance.

### ■ Fire frequency and C stocks over multiple disturbance cycles

The C stocks of an ecosystem in a steady state are inversely proportional to the rate constants related to losses, such as those that occur through respiration or combustion (Olson 1963). Whereas Olson (1963) considered ecosystems in steady state, the same phenomenon occurs for the average ecosystem stocks over time or over broad areas (Smithwick *et al.* 2007). As fire frequency increases, the absolute and relative amount of C combusted per individual fire decreases, suggesting that as fire frequency increases, so too will average C stocks. However, using a model that simulates forest growth, mortality, decomposition, and fuel-dependent combustion, researchers can show that a low-frequency, high-severity fire regime stores substantially more C over time than a high-frequency, low-severity fire regime (mean C stocks increased by 40% as the mean fire-return interval was increased from 10 to 250 years; Figure 5). The reason for this is explained by the first principles outlined by Olson (1963). Fractional combustion is, by nature, more constrained than fire frequency. In our example, although fire interval increased from 10 years to 250 years, fractional combustion of ecosystem C for a semiarid ponderosa pine forest only increased from 9% to 18% (Figure 5). To have parity in C stocks across these different fire intervals, fractional combustion per event would, at times, have to exceed 250% – clearly violating the conservation of mass. As long as wildfire does not cause lasting changes in site productivity or non-fire mortality, no forest system is exempt from this negative relationship between fire frequency and average landscape C storage. Although we chose to illustrate the response for a semiarid ponderosa pine forest typical of those considered for fuel reduction, the same relative response was observed when the simulations were run for mesic Douglas fir (*Pseudotsuga menziesii*) forests parameterized for higher production and decomposition rates.

Although stability of C stocks is desirable, stability is a function of spatial extent. In the case of a single forest stand, C stocks under the frequent, low-severity fire regime are more stable than those under an infrequent, high-severity fire regime. However, the fluctuations in C stocks exhibited by a single stand become less relevant as one scales over time or over populations of stands experiencing asynchronous fire events (Smithwick *et al.* 2007). In other words, forests experiencing frequent fires lose

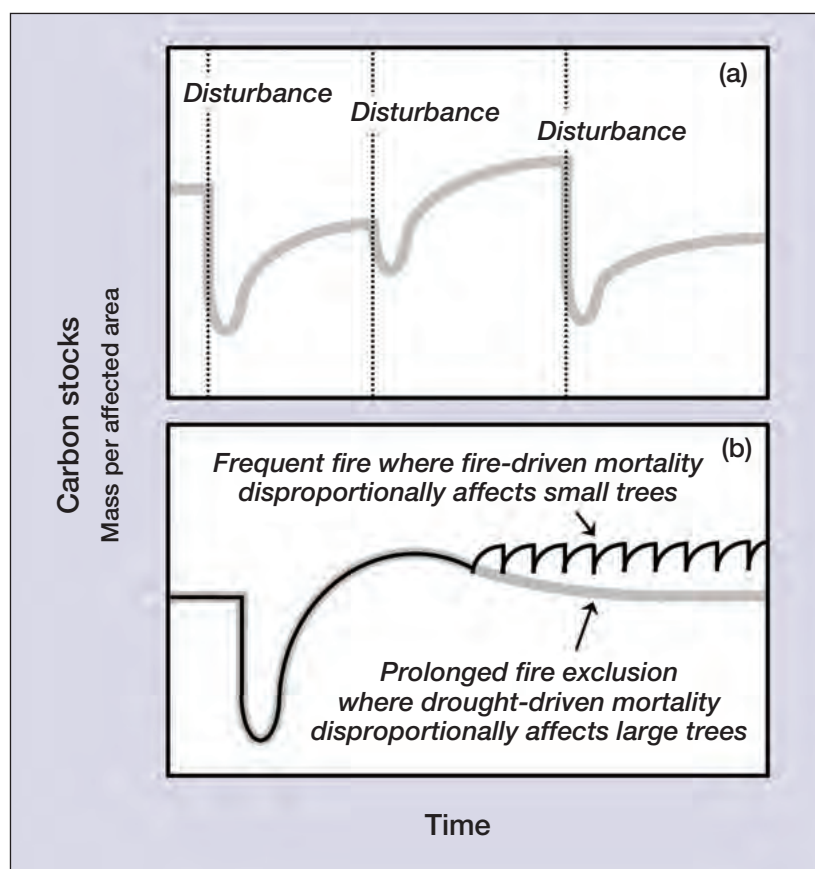


**Figure 5.** Total forest C stores simulated for a ponderosa pine forest in the eastern Cascades of Oregon experiencing three different hypothetical fire regimes. Black lines depict the C stores of five individual stands subject to random fire events. Blue lines mark the 500-year average of all five stands. As mean fire-return interval increases, the variation of C stores over time (or space by extension) increases, but so does the long-term average. For simplicity, we show the results of only five stands per fire regime; however, the mean trends do not change with additional simulations. Nearly identical patterns result when alternate forest types are used. We performed simulations using STANDCARB, as described in WebFigure 2 and in Harmon *et al.* (2009).

less C per fire event than forests experiencing infrequent fires, but the former do not store more C over time or across landscapes.

### ■ The capacity of fire and fuel-reduction treatments to alter equilibrium states

In the sections above, we have assumed that forests eventually succeed toward a site-specific dynamic equilibrium of growth and mortality. Although the concept of a site-specific carrying capacity usefully underlies many of the models of forest development, it is worth considering situations where disturbances might initiate alternate steady states by effecting changes in growth, mortality, or combustibility that persist through to the next disturbance.



**Figure 6.** Hypothetical examples of how disturbances could initiate alternate steady-state C stocks. (a) Illustration of what C stocks might look like if long-term successional trajectories were contingent more on seed availability at the time of fire than they were on fixed site conditions, as suggested by Kashian *et al.* (2006). (b) Illustration of how frequent fires could shift mortality away from larger trees and toward smaller trees, thus increasing steady-state C stocks, as suggested by North *et al.* (2009).

A simple example of disturbance-altering, long-term forest growth involves the loss in soil fertility that can accompany certain high-severity fires (Johnson and Curtis 2001; Bormann *et al.* 2008). Another mechanism by which disturbance can initiate changes in steady-state C stocks involves the persistent changes in tree density that may follow some disturbance events. For instance, Kashian *et al.* (2006) determined that forest biomass in the lodgepole pine (*Pinus contorta*) forests of Yellowstone National Park was relatively insensitive to changes in fire frequency but very dependent on the density to which forests grew after fire. In a system where long-term successional trajectories are contingent more on forest condition at the time of disturbance (eg serotinous seed availability) than on permanent site conditions, C stocks could well stabilize at different levels after different disturbances, as illustrated in Figure 6a.

A final example of how changes in disturbance regime could persistently alter equilibrium between growth and mortality involves size-dependent mortality in the semi-arid conifer forests of the Sierra Nevada (Smith *et al.* 2005). Both Fellows and Goulden (2008) and North *et al.*

(2009) found fewer large trees and lower overall biomass in current fire-excluded forests than were believed to exist at these locations before fire exclusion. These authors suggest that small trees are disproportionately vulnerable to fire mortality, and large trees are disproportionately vulnerable to pathogen- and insect-based mortality; therefore, as biological agents replace fire as the primary cause of mortality, the number of large trees decreases accordingly. Under such scenarios, the thinning of small trees combined with frequent burning could, over time, increase biomass by maintaining a greater number of larger trees (see Figure 6b). However, not all studies support the notion that fire exclusion reduces stand-level biomass (Bouldin 2008; Hurteau *et al.* 2010). Specifically, another study conducted by North *et al.* (2007) in the Sierra Nevada found that net losses in large-diameter trees between 1865 and 2007 were more than compensated for by the infilling of small-diameter trees, such that total live-wood volume remained unchanged over this period of fire suppression. Furthermore, Hurteau and North (2010) reported that fire-suppressed control plots aggraded as much C over 7 years as did comparable thinned plots.

Presuming that maximum steady-state C stocks are not dictated entirely by permanent site qualities and depend, at least in some part, on the nature and timing of disturbance, it is conceivable that prescriptions such as fuel reduction and prescribed fire could eventually elevate (or reduce) C stocks at a single location slightly beyond what they would be under a different disturbance regime (Hurteau *et al.* 2010). However, exactly how stable or self-reinforcing this alternate state is remains unknown.

### ■ Additional considerations

The purpose of this paper is to illustrate the basic biophysical relationships that exist between fuel-reduction treatments, wildfire, and forest C stocks over time. Understanding these dynamics is necessary for crafting meaningful forest C policy; however, it is not by itself sufficient. A full accounting of C would also include the fossil-fuel costs of conducting fuel treatments, the longevity of forest products removed in fuel treatments, and the ability of fuel treatments to produce renewable “bioenergy”, potentially offsetting combustion of fossil fuels. A detailed consideration of these factors is beyond the scope of this paper, but it is worth pointing out some limits of their contribution. First, the fossil-fuel costs of conduct-



ing fuel treatments are relatively small, ranging from 1–3% of the aboveground C stock (Finkral and Evans 2008; North *et al.* 2009; Stephens *et al.* 2009b). Second, only a small fraction of forest products ever enters “permanent” product stocks; this is especially true for the smaller-diameter trees typically removed during fuel treatments. Primarily, half-lives of forest products (7–70 years) are not significantly different than the half-life of the same biomass left in forests (Krankina and Harmon 2006). Third, the capacity of forest biofuels to offset C emissions from fossil-fuel consumption is greatly constrained by both transportation logistics and the lower energy output per unit C emitted as compared with fossil fuel (Marland and Schlamadinger 1997; Law and Harmon 2011).

### ■ Conclusions

The empirical data used in this paper derive from semi-arid, fire-prone conifer forests of the western US, which are largely composed of pine, true fir (*Abies* spp), and Douglas fir. These are the forests where management agencies are weighing the costs and benefits of up-scaling fuel-reduction treatments. Although it would be imprudent to insist that the quantitative responses reported in this paper necessarily apply to every manageable unit of fire-prone forest in the western US, our conclusions depend not so much on site-specific parameters but rather on the basic relationships – between growth, decomposition, harvest, and combustion – to which no forest is exempt. To simply acknowledge the following – that (1) forest wildfires primarily consume leaves and small branches, (2) even strategic fuels management often involves treating more area than wildfire would otherwise affect, and (3) the intrinsic trade-off between fire frequency and the amount of biomass available for combustion functions largely as a zero-sum game – leaves little room for any fuel-reduction treatment to result in greater sustained biomass regardless of system parameterization. Only when treatment, wildfire, or their interaction leads to changes in maximum biomass potential (ie system state change) can fuel treatment profoundly influence C storage.

In evaluating the effects of wildfire and fuel-reduction treatments on forest C stocks across various spatial and temporal scales, we conclude that:

- (1) Empirical evidence shows that most pyrogenic C emissions arise from the combustion of surface fuels, and because surface fuel is combusted in almost all fire types, high-severity wildfires burn only 10% more of the standing biomass than do the low-severity fires that fuel treatment is intended to promote (Figure 1).
- (2) Model simulations support the notion that forests subjected to fuel-reduction treatments experience less pyrogenic emissions when subsequently exposed to wildfires. However, across a range of treatment inten-

sities, the amount of C removed in treatment was typically three times that saved by altering fire behavior (Figure 2).

- (3) Fire-spread simulations suggest that strategic application of fuel-reduction treatments on as little as 1% of a landscape annually can reduce the area subject to severe wildfire by 50% over a 20-year period. Even so, the protection of one hectare of forest from wildfire required the treatment of 10 hectares, owing not to the low efficacy of treatment but rather to the rarity of severe wildfire events (Figure 3).
- (4) It is reasonable to expect that after a forest-replacing fire, the decomposition of fire-killed trees exceeds NPP, driving NEP below zero. By contrast, the deliberate removal of necromass in fuel-reduction treatments could result in a period of elevated NEP. However, despite marked differences in post-disturbance NEP, it is possible for average C stocks to be identical for these two disturbance types (Figure 4).
- (5) Long-term simulations of forest growth, decomposition, and combustion illustrate how, despite a negative feedback between fire frequency and fuel-driven severity, a regime of low-frequency, high-severity fire stores more C over time than a regime of high-frequency, low-severity fire (Figure 5).
- (6) The degree to which fuel management could possibly lead to increased C storage over space and time is contingent on the capacity of such treatments to increase maximum achievable biomass through mechanisms such as decreased non-fire mortality or the protection from losses in soil fertility that are sometimes associated with the highest-severity fires (Figure 6).

There is a strong consensus that large portions of forests in the western US have suffered both structurally and compositionally from a century of fire exclusion and that certain fuel-reduction treatments, including the thinning of live trees and prescribed burning, can be effective tools for restoring historical functionality and fire resilience to these ecosystems (Hurteau *et al.* 2010; Meigs and Campbell 2010). Furthermore, by reducing the likelihood of high-severity wildfire, fuel-reduction treatments can improve public safety and reduce threats to the resources provided by mature forests.

On the basis of material reviewed in this paper, it appears unlikely that forest fuel-reduction treatments have the additional benefit of increasing terrestrial C storage simply by reducing future combustive losses and that, more often, treatment would result in a reduction in C stocks over space and time. Claims that fuel-reduction treatments reduce overall forest C emissions are generally not supported by first principles, modeling simulations, or empirical observations. The C gains that could be achieved by increasing the proportion of large to small trees in some forests are limited to the marginal and variable differences in biomass observed between fire-sup-

pressed forests and those experiencing frequent burning of understory vegetation.

Emerging policies aimed at reducing atmospheric CO<sub>2</sub> emissions may well threaten land managers' ability to apply restoration prescriptions at the scale necessary to achieve and sustain desired forest conditions. For this reason, it is imperative that scientists continue research into the processes by which fire can mediate long-term C storage (eg charcoal formation, decomposition, and community state change) and more accurately quantify the unintended consequences of fuel-reduction treatments on global C cycling.

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