Agronomic rates of compost application for California croplands and rangelands to support a CDFA Healthy Soils Incentives Program

Kelly Gravuer, PhD Candidate,
Graduate Group in Ecology and Graduate Student Assistant
University of California, Davis
California Department of Food and Agriculture

Prepared in coordination with Amrith (Ami) Gunasekara, PhD
Liaison to the Environmental Farming Act Science Advisory Panel
California Department of Food and Agriculture, Sacramento
A report for the Environmental Farming Act Science Advisory Panel

Draft (Version 1.0 – 1/5/2016)

Table of Contents

Executive Summary

As part of Governor Brown's Healthy Soils Initiative, the California Department of Food and Agriculture (CDFA) is planning to establish a financial incentivize program for California's farmers and ranchers to implement practices that improve soil health and reduce greenhouse gas (GHG) emissions. These incentives would be based on the COMET-Planner tool, which estimates GHG reductions from agricultural management practices. However, one agricultural practice with considerable soil health improvement and GHG reduction potential is not yet included in the COMET-Planner tool. The application of compost to croplands and rangelands is an important management practice that can improve soil health. In order to make this management practice included in any future incentive program by CDFA, agronomic compost application rates need to be established.

At the recommendation of the Environmental Farming Act Science Advisory Panel, CDFA convened a subcommittee of scientific experts to propose best-available scientific-based agronomic rates of compost application. This expert group proposed distributing composts into two major categories: those with higher nitrogen (C:N ≤ 11) and those with lower nitrogen (C:N > 11) content. The group also proposed dividing California cropping systems into two major types (annual crops and tree crops) and considering croplands and rangelands separately.

The subcommittee recommended a maximum agronomic rate of 8 moist (i.e., as purchased) tons of compost/acre/year based on current grower practices and best-available science. Agronomic rates of moist compost application for croplands were: for annual crops, 3-5 tons/acre/year for higher nitrogen (C:N ≤ 11) compost and 8 tons/acre/year for lower nitrogen (C:N > 11) compost; and for tree crops, 2-4 tons/acre/year for higher nitrogen compost and 6-8 tons/acre/year for lower nitrogen compost.

Agronomic rangeland application rates were recommended at 5-10 tons/acre for higher nitrogen compost and 15-30 tons/acre for lower nitrogen compost. However, because specific field data on rangeland compost application in California is still very limited, it is vital to continue documenting effects of this practice and adjust agronomic rates according to site specifications. Additional information on the science and logic on how these rates were proposed by the expert group is described in this report.

Introduction

In the 2015-16 proposed budget, Governor Brown recognized the importance of soil health and directed the California Department of Food and Agriculture (CDFA) to coordinate a new initiative to support and enhance this critical resource. The budget language stated "As the leading agricultural state in the nation, it is important for California's soils to be sustainable and resilient to climate change. Increased carbon in soils is responsible for numerous benefits including increased water holding capacity, increased crop yields and decreased sediment erosion. In the upcoming year, the Administration will work on several new initiatives to increase carbon in soil and establish long term goals for carbon levels in all California's agricultural soils. CDFA will coordinate this initiative under its existing authority provided by the Environmental Farming Act".

Consistent with the Governor's initiative, now titled the Healthy Soils Initiative, CDFA worked with several state agencies to identify short and long-term actions that could improve soil health in California to ensure agricultural sustainability and food security (https://www.cdfa.ca.gov/EnvironmentalStewardship/ pdfs/ShortTermActions.pdf). One of the actions identified was to incentivize management practices that build the carbon content in soils. Increasing the carbon content of soils has been scientifically shown to lead to greater agricultural sustainability and ensure food security, especially in light of climate change. CDFA plans to implement a cost-share incentives program using management practice standards established by the United States Department of Agriculture (USDA) Natural Resources Conservation Services (NRCS). The CDFA program would include soil health-promoting management practices that also reduce greenhouse gas (GHG) emissions. The quantification of GHG reductions is feasible with the recently developed COMET-Planner[1] tool.

An agricultural management practice with significant potential to increase soil carbon content and reduce GHG emissions to the atmosphere in California is not yet being included in the NRCS Management Practice Standards or COMET-Planner. This management practice is the application of compost to croplands and rangelands. This practice can sequester carbon in soils and plants by promoting increased soil microbial and plant biomass[2,3], with part of this carbon eventually sequestered as stabilized soil organic matter called humic substances[4,5]. It can also indirectly achieve large GHG emission reductions[6] by providing a market for compost, spurring expansion of composting facilities and organic waste diversion from landfills that produce methane. Methane as a GHG is 28 times more potent than carbon dioxide. Aerobic composting allows the carbon in carbon-based animal and plant source materials to be stabilized into carbon compounds that generally decompose slowly after the compost is applied to land and stimulates a biological process that sequesters carbon into stable long-term carbon fractions. These carbon fractions offer numerous benefits such as increasing the water holding capacity of soils.

Because of the significant potential benefits of compost application and greenhouse gas reductions in California, CDFA must determine "agronomic rates" of compost application to support an incentives program. CDFA will not be able to support unlimited rates of compost application requested by farmers and ranchers given the limited amount of funding available as incentives, as well as the need to ensure that environmental concerns are addressed and that GHG reductions are obtained. In addition, these rates need to be feasible for farmers to implement, based on compost cost, other management needs, and potential changes in yield (if any). The amount of anticipated greenhouse gas reduction corresponding to these agronomic rates can then be estimated based on a model from the California Air Resources Board[7], making this practice comparable to other management practice standards listed in COMET-Planner.

Methodology

On July 17, 2015, CDFA convened a meeting of the Environmental Farming Act Science Advisory Panel (EFA SAP) to discuss the application of compost to California croplands and rangelands. The EFA SAP is a group of farmers and scientists who provide scientific guidance to the Secretary of CDFA and acts as a platform for public comment. The EFA SAP functions under the authority of the Environmental Farming Act of 1995 (https://www.cdfa.ca.gov/Environmental Stewardship/pdfs/EnvironmentalFarmingAct.pdf). The meeting was open to the public and was well-attended by a variety of stakeholders. Attendees at the meeting recommended that CDFA convene a subcommittee of compost experts (from academia and state agencies) to evaluate and propose agronomic rates of compost application, which could then be considered for review by the EFA SAP, and subject to public comment and proposed to the Secretary of CDFA to implement as part of any future Healthy Soil incentive program to build soil carbon.

On August 28, 2015, CDFA convened a meeting of this compost subcommittee (herein called expert group). The expert group consisted of university experts in soil science, compost management and agronomy and included scientists from several pertinent state agencies such as CalRecycle, CDFA and the Central Valley Regional Water Quality Control Board (a complete list of participants can be found at the end of this report). The goal of this meeting was to determine how to address agronomic compost application rates given the diversity of cropping systems in California. A second meeting of the expert group was held on September 30, 2015.

Between the two meetings several literature reviews were conducted to evaluate the best available science that would support agronomic rates for compost application to support a CDFA incentives program on soil health. The Results section summarizes the findings of the literature reviews and proposed compost application rates recommended by the expert group.

Results

A major outcome of the expert group meeting on August 28, 2015 was consensus that there is too much variation in the scientific data within both “croplands” and “compost” to define a single application rate. The expert group felt that “croplands” could be usefully divided into annual crops and tree crops and that both conventional and organic management systems should be considered for each of these production systems. Rangelands have different considerations and warranted their own separate category. “Compost” eligible for the program should be of the “fully composted” type only and could be divided into two further categories (carbon: nitrogen ratio less than and greater than approximately 11). This differentiation, according to the expert group, would separate compost that provided more nitrogen at a faster rate (low C:N) vs. those that provided less nitrogen at a slower rate (high C:N). The group suggested that compost with C:N greater than 11 could be thought of as a practice that is *in addition to* the nutrient management system on the farm, whereas compost with C:N less than 11 could be thought of as a practice that is *part of* the nutrient management system on the farm. In total, the group identified ten application rates for a CDFA incentives program on building soil carbon (Figure 1).

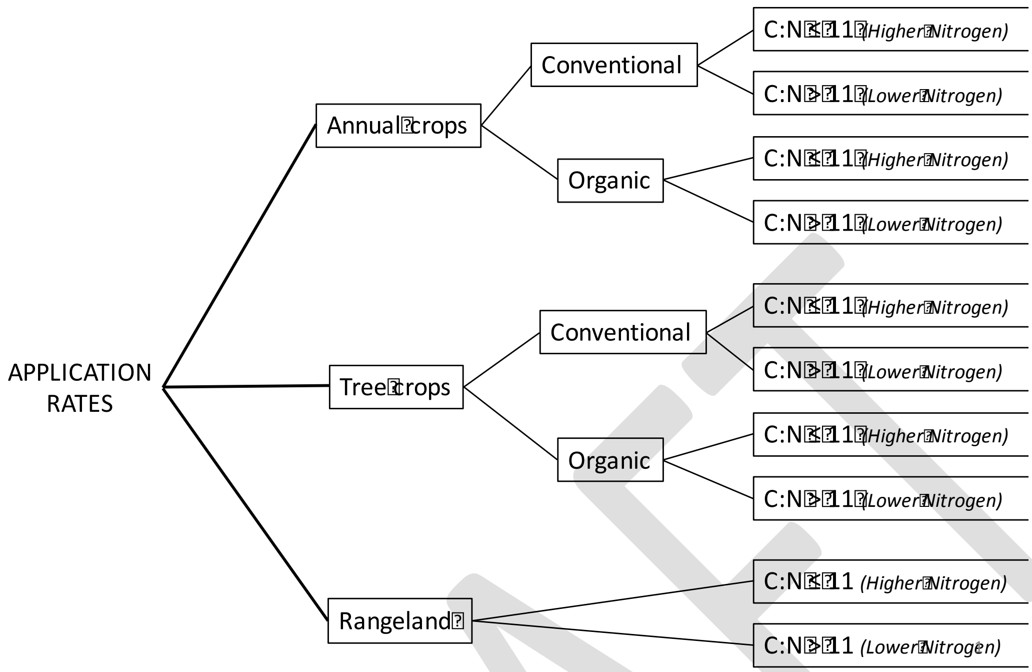

Figure 1. Distribution of application rates to define, as established at August 28, 2015 expert group meeting.

The expert group agreed to a general approach of setting the upper application limit of each application rate range based on best-available scientific data on the potential environmental impact(s) of greatest concern.

Agronomic compost application rates for croplands

The expert group defined the environmental impact of greatest concern to be the potential of increased nitrate leaching to ground water for croplands. Most composts contain small amounts of nitrate as well as other nitrogen compounds that could eventually be converted to nitrate by resident soil microbes. As such, a scientific literature review was conducted to develop estimates of the nitrogen available for conversion to nitrate over time in the two types of composts.

<u>Estimating nitrogen mineralization from compost</u>: Nitrogen in compost can be divided into three main types: nitrate [and nitrite which converts to nitrate rapidly] (NO_3^-; inorganic nitrogen), ammonium (NH_4^+; inorganic nitrogen that can be quickly converted to nitrate by resident soil microbes), and organically-bound nitrogen (nitrogen attached to carbon-containing compounds, which can be slowly converted to ammonium and then nitrate by resident soil microbes). Ammonium and nitrate are the forms of nitrogen typically provided by synthetic fertilizers in conventional agriculture systems (along with urea, which is quickly hydrolyzed to ammonium once applied). The literature review included estimating the rate of

ammonium + nitrate release by compost, and then assuming that the behavior of that ammonium + nitrate would be similar to that of an equivalent amount of applied synthetic ammonium + nitrate (in terms of its potential for uptake by plants or microbes vs. storage in the soil vs. leaching vs. other loss pathways)[i]. The comparison of nitrogen in compost to synthetic fertilizers was made simply to mimic soil physio-chemical behaviors of the nitrogen and not compare the amendment to synthetic fertilizers. It should be noted that this comparison is very different than assuming that adding a certain weight of compost is equivalent to adding the same weight of synthetic fertilizer, as the total ammonium + nitrate available from compost in the year of application tends to be at most 0.3% of its total weight.

Estimating the rate of ammonium + nitrate release by compost requires three pieces of information: the amount (by weight) of ammonium + nitrate in the compost, the amount (by weight) of organically-bound nitrogen in the compost, and a model for the rate at which this organically-bound nitrogen will be converted (mineralized) to ammonium + nitrate. Estimates for the first two information needs (average amounts of ammonium + nitrate and organically-bound nitrogen) were obtained using a CalRecycle database of lab analyses for 1364 compost samples from the southwestern U.S. Composts were first divided into two categories (C:N ≤ 11 and C:N > 11) and average values of these quantities were calculated for each category separately; these averages were medians to avoid undue influence of extreme values (Table 1).

Table 1. Average (median) pounds (lbs) of nitrogen per ton of <u>dry compost</u> and average moisture content for higher nitrogen (C:N ≤ 11) and lower nitrogen (C:N > 11) compost types, as calculated from CalRecycle database of 1364 compost samples.

	Higher N compost (C:N ≤ 11)	Lower N compost (C:N > 11)
Lbs N as ammonium (NH_4^+)	1.43	0.51
Lbs N as nitrate (NO_3^-)	0.12	0.07
Lbs N as organically-bound N	38.12	26.43
Moisture content	27.11%	34.14%

A scientific literature review was completed to address the release of nitrogen from compost. A model for the rate at which organically-bound nitrogen in compost is mineralized to ammonium + nitrate was developed. The literature review was focused on scientific journal articles that synthesized many individual studies and/or studies that were specific to California[8–13]. For the

[i] This is an environmentally conservative assumption. Our estimates of nitrate potentially available for leaching from compost are *at the high end of the possible range*, as it is likely that compost will change soil properties in a way that allows less nitrate to be leached per pound of ammonium + nitrate applied as compared to un-amended fields. Although ammonium + nitrate derived from compost will behave the same as ammonium + nitrate from synthetic fertilizers, the soil matrix into which they are released (which strongly influences their fate of uptake vs. storage vs. leaching vs. loss by other means) will be different as a result of the compost addition. For example, compost generally improves soil water holding capacity, such that less water – potentially carrying nitrate – may leach below the crop root zone in compost-amended fields. However, because the amount of this reduction is highly dependent on soil type along with a range of other management factors, we do not believe it can be quantified reliably at this time and did not attempt to do so.

higher nitrogen type of compost (C:N ≤ 11), studies suggested that 5-15% (average ≈ 10%) of the organically-bound nitrogen would be mineralized in the first year (i.e., the year of application), with the percentage of remaining organically-bound nitrogen mineralized declining by half each subsequent year. Approximately 10% of the organically-bound nitrogen would be mineralized in the first year, 5% of the remaining organically-bound nitrogen in the second year, 2.5% of the remaining organically-bound nitrogen in the third year, etc. For the lower nitrogen type of compost (C:N > 11), studies suggested that 2-7% (average ≈ 5%) of the organically-bound nitrogen would be mineralized in the first year, with a similar pattern of mineralization percentage decline in subsequent years. At a second expert group meeting held on September 30, 2015, the expert group verified that the model was in agreement with existing scientific findings.

Comparing nitrogen from compost to recommended plant nitrogen requirements: With the information noted above, it is possible to estimate the amount of ammonium + nitrate released from compost in a given year following its application (or the cumulative amount released over a chosen number of years). To determine whether this amount would represent a significant addition of ammonium + nitrate to the landscape compared to the plant required nitrogen recommendations that are typically applied each year, plant required nitrogen recommendations for major California crops were reviewed. These recommendations are the result of an intensive literature review conducted by experts at the University of California, Davis in collaboration with CDFA's Fertilizer Research and Education Program (FREP) and are accessible at http://apps.cdfa.ca.gov/frep/docs/Guidelines.html. Plant required nitrogen recommendations were averaged across crops within the two major types: annual crops and tree crops. For annual fruit and vegetable crops (including processing tomatoes, broccoli, lettuce, strawberries, cauliflower, and corn), an average of 161 pounds of nitrogen per acre per year was recommended (with a high of 270 lbs/acre for corn). For established tree crops (including established almonds, walnuts, citrus, pistachios, and plums), an average of 115 pounds of nitrogen per acre per year was recommended (with a high of 380 lbs/acre for almonds). These numbers allowed for the estimated amount of ammonium + nitrate released for a particular application rate, compost type, and crop type to be expressed in units of "% of total plant required nitrogen represented by compost" (Box 1).

Box 1. Example of calculations to determine the percentage of total plant required nitrogen represented by compost. In this report, application rate recommendations for compost are in terms of "tons moist compost" to allow easy comparison with current compost application rates used by growers. However, % moisture varies widely among composts therefore, the final rate recommendations will be in terms of "tons dry compost", with the grower and compost facility responsible for determining the equivalent moist compost application rate based on the % moisture of the specific compost batch purchased.

<u>Example 1</u>: Apply lower N compost (C:N > 11) to tree crop

- N released by compost in year 1: 1.91 lbs per ton dry compost (1 ton = 2000 lbs) [ammonium-N + nitrate-N + 5% of organically-bound N]
- Average total N required for tree crops: 115 lbs/acre
- Average % moisture of lower N compost = 34.14%
- If applying **<u>5 moist tons</u>** of lower N compost per acre :
  - 5*(1- 0.3414) = 3.29 tons dry compost equivalent
  - 3.29 * 1.91 = 6.27 tons N applied per acre
  - 6.27 / 115 = <u>*5.5% of total required N added by compost*</u>

<u>Example 2</u>: Apply higher N compost (C:N ≤ 11) to annual crop

- N released by compost in year 1: 5.36 lbs per ton dry compost (1 ton = X lbs) [ammonium-N + nitrate-N + 10% of organically-bound N]
- Average total N required for annual crops: 161 lbs/acre
- Average % moisture of higher N compost = 27.11%
- If applying **<u>4 moist tons</u>** of higher N compost per acre :
  - 4*(1- 0.2711) = 2.92 tons dry compost equivalent
  - 2.92 * 5.36 = 15.6 tons N applied per acre
  - 15.6 / 161 = <u>*9.7% of total required N added by compost*</u>

With this framework, the calculation could also be used for other analyses: a percentage of the total nitrogen fertilizer recommendation to be represented by compost could be specified and the corresponding compost application rate determined (Table 2).

Table 2. Proposed agronomic rates for compost application to croplands. For the N composts with a C:N ratio > 11 (lower N*), composts with C:N ratio > 20-25 are likely to have negligible nitrogen release and may result in nitrogen immobilization. Therefore, as compost C:N increases, it becomes more important to monitor plant and soil conditions after application to ensure there is adequate nitrogen supply for the crop. The rates to use for the proposed incentives program are the "equivalent dry compost application rates"(†), which should be converted to corresponding moist compost application rates on a batch-specific basis using moisture data from the compost facility.

Crop Type	Compost Type	Moist Compost Application Rate (tons/acre)	Equivalent Dry Compost Application Rate (tons/acre)†	% of total plant required N represented by rate
Annual	Higher N (C:N ≤ 11)	3 – 5	2.2 – 3.6	7.3 – 12.1%
Annual	Lower N (C:N > 11)*	8	5.3	8.1%
Tree	Higher N (C:N ≤ 11)	2 – 4	1.5 – 2.9	6.8 – 13.6%
Tree	Lower N (C:N > 11)*	6 – 8	4.0 – 5.3	8.6 – 11.4%

At the second expert group meeting on September 30, 2015, the assembled experts confirmed that the initially proposed rates, with minor modifications that are reflected in Table 2, were reasonable agronomic rates to be used in a CDFA incentive program on soil health.

These rates that would be incentivized by a CDFA healthy soils incentive program would be the same for organic and conventional systems (see Organically-managed croplands section under Other Considerations). The recommended rates do not limit farmers from adding additional compost since these recommended rates have been established on an agronomic and environmental basis to solely support a CDFA healthy soils incentive program.

Agronomic compost application rates for rangelands

In California, the benefits and potential drawbacks of compost application have received far less study on rangelands than on croplands. So far, results from two northern California sites (Yuba County and Marin County, average annual precipitation 730 mm and 950 mm respectively) have been published[3,16,17]. At these sites, adding 31 tons/acre of compost (C:N = 11) resulted in C sequestration of 51 ± 77 to 333 ± 52 g C/m^2 over three years, without accounting for the C directly added by the amendment[3]. However, many scientists, including the expert group, have cautioned against extrapolating these results to the full extent of California rangelands, given the considerable diversity of climates and soils throughout the state[18,19]. Thus, while these initial northern California results are encouraging, studies at additional sites across California's climate and soil gradients – as well as with different types of composts (e.g., higher and lower C:N) – are necessary to understand the range of potential C sequestration rates that may be achieved.

Uncertainties about the drawbacks of rangeland compost application are even greater than the uncertainties about its (statewide) C sequestration benefits. In discussions within stakeholder meetings, peer review comments on external documents[20,21], and the expert group, three potential drawbacks predominate. First, the potential for increased nitrate leaching to groundwater was mentioned. Second, the potential for declines in plant diversity because nutrient addition could disproportionately favor certain plant species was noted. Thirdly, the stream-dissected sloped rangeland landscape combined with the considerable phosphorus content in many composts raised the concern of phosphorus movement into streams, which could lead to eutrophication (see "Other Considerations" section for discussion of phosphorus). As described below, specific research is not widely available to assess any of these three concerns, but some research studies related to the second concern (plant diversity) provides data on which to define preliminary rangeland application rates.

Potential impacts on nitrate: For nitrate leaching, rangelands would be expected to intercept more of the available nitrogen released from compost than croplands, due at least in part to a greater spatial and temporal extent of plant cover. However, no direct field measurements of nitrate leaching from compost-amended rangelands are available. For the northern California sites, Ryals *et al.*[17] used the DAYCENT model to estimate nitrate leaching in their study. The DAYCENT estimate was approximately 8.9 lbs NO_3-N/acre/year for the first 10 years post-application, which equates to approximately 40% of the N released from the compost leaching out as nitrate over that period (89 lbs NO_3-N/acre of the estimated 222 lbs N/acre released). As we found for croplands, leaching rates were considerably lower for simulations of C:N = 20 and C:N = 30 composts than they were for the C:N = 11 compost that was used in the field study. These estimates now urgently require field-validation and testing at other sites.

Potential impacts on plant diversity: The plant diversity issue was raised by several stakeholders. California rangelands support over 400 plants of conservation concern[22,23] and a number of rangeland wildlife species, some of which are also imperiled, require specific plants and/or vegetation structure for their food and habitat[24–26]. Concerns about the impact of compost addition on plant diversity are grounded in a fairly large body of studies that have documented significant changes in plant community composition – and usually decreases in diversity – in response to synthetic N fertilizer addition[29]. Typically, adding N increases grass biomass more so than forb biomass, such that a few highly-responsive grass species (mostly non-native) can outcompete many of the forbs (mostly native).

However, most of these studies have applied fairly high rates of N (80-100 lbs N/acre/year). There is a lack of scientific peer reviewed studies in California grasslands that have added a range of N rates to determine a threshold rate of N addition above which diversity is likely to decline. A few studies have attempted to determine N "critical loads" at which effects on the ecosystem are discernable[30–32]. These studies suggested that a critical load for California grasslands could be 6-9 lbs N/acre/year, but they are based on limited observational data along an N deposition gradient in serpentine grasslands. Because nutrient-poor serpentine grasslands may be more sensitive to nutrient addition than other California grassland types, more research is needed to evaluate whether this constitutes a basis for a compost application rate upper limit that would be relevant to most California rangelands.

Defining rates based on potential plant diversity impacts: As a preliminary strategy for setting an upper application limit for compost on rangelands, a literature review of organic amendment applications to rangelands was initiated. Studies meeting the following criteria were included in the review: (1) an organic amendment had been added to a semi-arid or Mediterranean-climate rangeland community (mostly grasslands, sometimes with scattered trees or shrubs), (2) the authors reported the %N of the amendment and enough information to assign it to the "high N" (C:N ≤ 11) or "low N" (> 11) C:N category described above, and (3) plant community diversity had been measured at some point after adding the amendment and compared to that of comparable control plot(s). In total, nine non-redundant studies fit the review criteria; five of which had used non-composted amendments. Most of the studies (including those of composted and non-composted amendments) had applied the amendment at multiple rates, providing 35 study x rate data points, nine of which represented composted amendments. Across these studies, the plant community was observed an average of four years after amendment application. Using the C:N and %N data provided in the studies. The same mineralization model used for croplands (described above) was then used to estimate the cumulative amount of available nitrogen that would have been released from the amendment by the time the plant diversity data was collected. The data points were then sorted by this estimate of nitrogen released (Table 3).

Classification tree analysis suggested that 36 lbs available N/acre was the threshold value that best separated treatments in which plant diversity declined from those in which it did not. Above 65 lbs available N/acre, the likelihood of plant diversity decline becomes significant, suggesting that this value should be the maximum application rate considered. For the rate determinations, slightly more conservative values of 30 and 60 lbs available N/acre were used.

The CalRecycle database estimates of average properties of higher N and lower N composts (Table 1) were used to translate these N thresholds into compost application rates (Table 4). For each type of compost, the "recommended" rate is equivalent to 30 lbs cumulative available N per acre five years post-application, attempting to strike a balance between rates at which impacts on plant diversity would be reasonably unlikely and rates that would promote significant C sequestration. This "recommended" rate would be appropriate for most eligible rangelands (see eligibility discussion below). The "high end" rate is equivalent to 60 lbs cumulative available N per acre five years post-application, allowing for more C sequestration but with some risk of impacting plant diversity. This "high end" rate would be appropriate to situations such as degraded rangelands with few native plant species, vegetation restoration sites (e.g., mines), and perhaps post-fire rangelands, where initial soil N may be lower.

Table 3. Literature review of organic amendment additions to semi-arid rangelands, sorted by N released at time of plant diversity measurement.

Amendment Type	Study	Mg/ha applied	Amendment N Category	Years between application & measurement	Inorganic N (lbs per ton compost)	Organic N (lbs per ton compost)	Available lbs N released/acre at time of measurement	Plant diversity decrease
non-composted	Pierce et al. 1998[33]	5	Lower N	2	0.34	0.24	0.52	N
non-composted	Pierce et al. 1998[33]	10	Lower N	2	0.34	0.24	1.04	N
non-composted	Pierce et al. 1998[33]	15	Lower N	2	0.34	0.24	1.56	N
non-composted	Pierce et al. 1998[33]	20	Lower N	2	0.34	0.24	2.08	N
non-composted	Pierce et al. 1998[33]	25	Lower N	2	0.34	0.24	2.60	N
non-composted	Pierce et al. 1998[33]	30	Lower N	2	0.34	0.24	3.12	N
non-composted	Pierce et al. 1998[33]	35	Lower N	2	0.34	0.24	3.64	N
non-composted	Pierce et al. 1998[33]	40	Lower N	2	0.34	0.24	4.16	N
non-composted	Sullivan et al. 2006[34]	2.5	Higher N	13	7.48	82.32	17.21	N
compost	Kowaljow et al. 2010[35]	40	Lower N	2	0.48	14.92	18.57	N
compost	Kowaljow et al. 2010[35]	40	Lower N	2	0.96	13.04	22.58	N
compost	Pedrol et al. 2010[36]	20	Lower N	0.5	2.36	43.44	26.65	N
non-composted	Sullivan et al. 2006[34]	5	Higher N	13	7.48	82.32	34.42	N
non-composted	Stavast et al. 2005[37]	12	Higher N	2	2.60	31.60	37.59	Y
compost	Kowaljow et al. 2010[35]	40	Lower N	2	1.06	29.94	38.41	N
compost	Martínez et al. 2003[38]	40	Lower N	3	1.82	33.38	54.82	Y
compost	Kowaljow et al. 2010[35]	40	Lower N	2	2.68	34.32	61.24	N
non-composted	Sullivan et al. 2006[34]	10	Higher N	13	7.48	82.32	68.85	Y
compost	Martínez et al. 2003[38]	80	Lower N	3	1.82	33.38	109.64	Y
non-composted	Sullivan et al. 2006[34]	21	Higher N	13	7.48	82.32	144.58	Y
compost	Ryals and Silver 2013[3]	70	Higher N	3	2.38	35.02	146.72	N*
non-composted	Martínez et al. 2003[38]	40	Higher N	3	4.02	48.98	158.30	Y
non-composted	Fresquez et al. 1990[39]	22.5	Higher N	3	7.38	89.82	163.30	N
compost	Martínez et al. 2003[38]	120	Lower N	3	1.82	33.38	164.46	Y
non-composted	Jurado-Guerra et al. 2013[40]	30	Higher N	2	6.22	75.78	167.89	Y
non-composted	Sullivan et al. 2006[34]	30	Higher N	13	7.48	82.32	206.54	Y
non-composted	Jurado-Guerra et al. 2013[40]	45	Higher N	2	6.22	75.78	251.83	Y
non-composted	Martínez et al. 2003[38]	80	Higher N	3	4.02	48.98	316.60	Y
non-composted	Fresquez et al. 1990[39]	45	Higher N	3	7.38	89.82	326.61	Y
non-composted	Jurado-Guerra et al. 2013[40]	60	Higher N	2	6.22	75.78	335.77	Y
non-composted	Stavast et al. 2005[37]	107	Higher N	2	2.60	31.60	343.17	Y
non-composted	Jurado-Guerra et al. 2013[40]	75	Higher N	2	6.22	75.78	419.72	Y
non-composted	Martínez et al. 2003[38]	120	Higher N	3	4.02	48.98	474.90	Y
non-composted	Jurado-Guerra et al. 2013[40]	90	Higher N	2	6.22	75.78	503.66	Y

non-composted	Fresquez et al. 1990[39]	90	Higher N	3	7.38	89.82	653.21	Y

*plant diversity data from Ryals et al. *in press* (as communicated by R. Ryals)

Table 4. Proposed agronomic rates for compost application to rangelands. "Recommended" rates are equivalent to 30 lbs cumulative available N per acre five years post-application and would be an appropriate starting point for most eligible rangelands. "High end" rates are equivalent to 60 lbs cumulative available N per acre five years post-application and would be appropriate in situations where plant diversity impacts are less of a concern (discussed above).

Compost Type	"Recommended" Moist Compost Application Rate (tons/acre)	"Recommended" Equivalent Dry Compost Application Rate (tons/acre)	"High end" Moist Compost Application Rate (tons/acre)	"High end" Equivalent Dry Compost Application Rate (tons/acre)
Higher N (C:N ≤ 11)	5	3.5	10	7.1
Lower N (C:N > 11)	15	9.8	30	19.6

Some types of rangeland are especially sensitive to nutrient addition and/or contain high concentrations of rare and threatened species. For example, impacts on species of conservation concern in serpentine grasslands have occurred at N addition rates that are one-fifth of the "recommended" compost rates identified here[30–32] (Table 4). *All such sensitive areas should be ineligible for compost addition incentives*. Stakeholders including The Nature Conservancy and the California Native Plant Society have prepared maps identifying these areas, which could easily be used to screen proposed projects. The expert group at the second CDFA meeting agreed with the need to avoid adding compost to these sensitive ecosystems. Therefore, additional ecologically-based eligibility exclusions should be considered for rangeland compost application.

Summary of compost application rates for croplands and rangelands

A summary of the recommend rates for compost application to support a CDFA incentive program on soil health is provided in Table 5 below.

Table 5. Recommendations of the expert group for compost application to agricultural lands distributed by type of agronomic system, C:N ratio and type of farming. The recommended rates do not limit farmers from adding additional compost since these recommended rates have been established on an agronomic and environmental basis to solely support a CDFA healthy soils incentive program. The rates to use for the proposed incentives program are the "equivalent dry compost application rates"(†), which should be converted to corresponding moist compost application rates on a batch-specific basis using moisture data from the compost facility. For rangelands, the lower end of the rate range is an appropriate starting point for most rangelands, while the higher end of the range could be appropriate in situations where plant diversity impacts are less of a concern (discussed above).

System	Management	Crop Type	Compost Type	Moist Compost Application Rate (tons/acre)	Equivalent Dry Compost Application Rate (tons/acre)†
Cropland	Conventional	Annual	Higher N (C:N ≤ 11)	3 – 5	2.2 – 3.6
Cropland	Organic	Annual	Higher N (C:N ≤ 11)	3 – 5	2.2 – 3.6
Cropland	Conventional	Annual	Lower N (C:N > 11)	8	5.3
Cropland	Organic	Annual	Lower N (C:N > 11)	8	5.3
Cropland	Conventional	Tree	Higher N (C:N ≤ 11)	2 – 4	1.5 – 2.9
Cropland	Organic	Tree	Higher N (C:N ≤ 11)	2 – 4	1.5 – 2.9
Cropland	Conventional	Tree	Lower N (C:N > 11)	6 – 8	4.0 – 5.3
Cropland	Organic	Tree	Lower N (C:N > 11)	6 – 8	4.0 – 5.3
Rangeland	--	--	Higher N (C:N ≤ 11)	5(–10)	3.5(–7.1)
Rangeland	--	--	Lower N (C:N > 11)	15(–30)	9.8(–19.6)

Other Considerations

Nitrous oxide (N_2O) emissions. An additional issue that was raised was whether compost application to croplands could cause increases in nitrous oxide (N_2O) emissions. This might be suspected because compost provides an additional organic carbon source for soil microbes, and organic carbon is one of the limiting factors for heterotrophic denitrification, one of the N_2O production pathways in soil. This anaerobic pathway is expected to be a significant contributor to N_2O emissions when soils are relatively saturated (> 80% water-filled pore space) and it may be limited by either carbon or nitrate under those conditions.

Under most other conditions, reactions related to nitrification including ammonia oxidation and nitrifier denitrification are believed to be the dominant contributor to N_2O emissions from California's agricultural soils[14,15]. These reactions are carried out by autotrophs that are not stimulated by organic carbon addition. Finally, all of these N_2O production pathways do tend to be stimulated by addition of ammonium, such that an increase in N_2O emissions may be noted when comparing compost-amended soil to an unamended control because of the ammonium provided by the compost. However, the impact of ammonium addition via compost would not be expected to be greater than that of addition of an equivalent amount of ammonium via synthetic fertilizer, and these effects can therefore be considered within the “percentage of recommendation” framework outlined above.

Organically-managed croplands. There is considerable variation among organic growers in the use of compost for plant nutrient provision; some growers apply substantial compost to supply a significant percentage of crop nutrient needs, whereas others may apply little to no compost and rely on other organic nutrient sources, such as manure, certain cover crops, and feather meal[10]. It is challenging, therefore, to define a compost application rate that would fit well into the nutrient management system of all organic growers. As such, at the second subcommittee meeting the group agreed that the application rates eligible for cost-share financial incentives could be the same for organic and conventional growers (Table 2), with the understanding that organic growers, in general, may apply greater amounts of compost in total, but are only eligible for a the same cost share incentives as conventional growers.

Phosphorus. For phosphorus-driven eutrophication concerns on rangelands, a site-specific risk factor analysis is an alternative strategy to across-the-board limits on application rates. Similar to the “phosphorus index” approach applied in many states to evaluate risk from phosphorus application to croplands[27], rangeland areas with low soil P that are at a considerable distance from waterways probably would not create significant risk and therefore might base their application rates on other concerns. For areas that do have one or both of these risk factors, a more detailed risk assessment can be conducted[27], and some or all of the risk could be mitigated by adjusting the compost application rate and/or using best management practices (BMPs) such as riparian buffers. Alternatively, potentially problematic areas of the property could simply be avoided if there are other more suitable areas. The American Carbon Registry’s Methodology for Compost Additions to Grazed Grasslands (Version 1.0)[28] recommends a site survey by a Qualified Expert (i.e., a Certified Rangeland Manager, NRCS Soil Conservationist or Qualified Extension Agent) before compost is applied to assess this and other risks.

Life cycle concerns. A frequently-raised question is whether the CO_2 emitted in transporting compost to the rangeland site would be greater than the C sequestered as a result of its application. This might be the case if considering only the C sequestered via biological activity on site, which for rangelands is estimated to be approximately 50% of the CO_2 emitted during transport based on a life cycle analysis using data from these northern California rangeland sites[6]. However, this balance depends on the system to which compost is applied and the methods used to make emissions estimates. For example, a California Air Resources Board study of compost application to croplands estimated that transport to the application site would emit 0.008 MT CO_2e per ton of composted feedstock while on-site soil C increases (estimated using biogeochemical process modeling rather than field data) would sequester 0.26 MT CO_2e per ton of composted feedstock, on average[7]. Furthermore, if increased demand for compost created by rangeland application is assumed to be directly responsible for increased diversion of organic waste from landfills and/or manure from slurry ponds into aerobic composting processes, then this practice reduces GHGs due to avoided methane emissions[6] which is 28 times more potent than carbon dioxide. Assessing this claim is beyond the scope of this report, as there are numerous other drivers of diversion of organic wastes and manures to composting in California, such that it is difficult to estimate the present and potential future contributions of rangeland demand.

Rangeland site assessments. For rangelands, an in-person site assessment by a qualified professional, as stipulated in the American Carbon Registry Protocol[28], is highly recommended in addition to using the agronomic rates. This professional should survey the site for species of conservation concern, identify any potential places where phosphorus transport poses a eutrophication risk, recommend BMPs to mitigate runoff, and assess other resource concerns as appropriate. Comprehensively evaluating a practice's potential effects on all natural resources is a standard NRCS procedure, and, as such, should be part of any Compost Addition to Rangelands Conservation Practice Standard.

Additional considerations for rangelands. First, five of the nine studies in the literature review involved non-composted organic amendments. Nitrogen mineralization is likely to be faster in non-composted than in composted amendments, such that levels of available N may be underestimated for non-composted amendments in Table 3.

Second, nitrogen is not the only soil nutrient that could increase with compost addition, as compost usually contains significant phosphorus, potassium, and other secondary plant nutrients as well. Here, rates were determined based on N release because there are more studies demonstrating N impacts on California grassland plant communities than there are for other nutrients [29]. However, other nutrients and indirect effects may have important consequences over the longer term[41].

Finally, it is important to consider the ecology of California rangeland plant communities when evaluating findings of "no impact" on their diversity. Many rangeland forb species form seed banks and only appear in years that are favorable for them. Any change in soil conditions may alter the degree of favorability of such years for these species, but this alteration may not be detected within the timeframe of most published studies. These dynamics suggest a precautionary approach to practices that could impact California rangeland plant diversity.

Literature Cited

1. Swan, A. *et al. COMET-Planner: Carbon and greenhouse gas evaluation for NRCS conservation practice planning*. (2014). at <http://www.comet-planner.com/COMET-Planner_Report_Final.pdf>
2. Kong, A. Y. Y., Six, J., Bryant, D. C., Denison, R. F. & van Kessel, C. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Sci. Soc. Am. J.* **69,** 1078 (2005).
3. Ryals, R. & Silver, W. L. Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecol. Appl.* **23,** 46–59 (2013).
4. Miltner, A., Bombach, P., Schmidt-Brücken, B. & Kästner, M. SOM genesis: microbial biomass as a significant source. *Biogeochemistry* **111,** 41–55 (2012).
5. Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K. & Paul, E. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Glob. Chang. Biol.* **19,** 988–995 (2013).
6. DeLonge, M. S., Ryals, R. & Silver, W. L. A lifecycle model to evaluate carbon sequestration potential and greenhouse gas dynamics of managed grasslands. *Ecosystems* **16,** 962–979 (2013).
7. California Air Resources Board. *Method for Estimating Greenhouse Gas Emission Reductions From Compost From Commercial Organic Waste*. (2011). at <http://www.arb.ca.gov/cc/protocols/localgov/pubs/compost_method.pdf>
8. Sullivan, D. M. *Estimating plant-available nitrogen from manure*. *Oregon State University Extension Catalog* **EM 8954-E,** (2008).
9. Pettygrove, G. S., Heinrich, A. L. & Crohn, D. M. *Manure nitrogen mineralization*. *University of California Cooperative Extension Manure Technical Bulletin Series* (2009). at <http://manuremanagement.ucdavis.edu>
10. Gaskell, M. *et al. Soil fertility management for organic crops*. (2006). at <http://anrcatalog.ucanr.edu/pdf/7249.pdf>
11. Hartz, T. K., Mitchell, J. P. & Giannini, C. Nitrogen and carbon mineralization dynamics of manures and composts. *HortScience* **35,** 209–212 (2000).
12. Havlin, J. L., Tisdale, S. L., Nelson, W. L. & Beaton, J. D. *Soil fertility and fertilizers: An introduction to nutrient management*. (Prentice Hall, 2014).
13. Amlinger, F., Götz, B., Dreher, P., Geszti, J. & Weissteiner, C. Nitrogen in biowaste and yard waste compost: Dynamics of mobilisation and availability - a review. *Eur. J. Soil Biol.* **39,** 107–116 (2003).
14. Hu, H.-W., Chen, D. & He, J.-Z. Microbial regulation of terrestrial nitrous oxide formation: understanding the biological pathways for prediction of emission rates. *FEMS Microbiol. Rev.* 1–21 (2015).
15. Zhu, X., Burger, M., Doane, T. A. & Horwath, W. R. Ammonia oxidation pathways and

nitrifier denitrification are significant sources of N2O and NO under low oxygen availability. *Proc. Natl. Acad. Sci. U. S. A.* **110,** 6328–6333 (2013).

16. Ryals, R., Kaiser, M., Torn, M. S., Berhe, A. A. & Silver, W. L. Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. *Soil Biol. Biochem.* **68,** 52–61 (2014).
17. Ryals, R., Hartman, M. D., Parton, W. J., DeLonge, M. S. & Silver, W. L. Long-term climate change mitigation potential with organic matter management on grasslands. *Ecol. Appl.* **25,** 531–545 (2015).
18. Booker, K., Huntsinger, L., Bartolome, J. W., Sayre, N. F. & Stewart, W. What can ecological science tell us about opportunities for carbon sequestration on arid rangelands in the United States? *Glob. Environ. Chang.* **23,** 240–251 (2013).
19. Sinsabaugh, R. L. *et al.* Soil microbial responses to nitrogen addition in arid ecosystems. *Front. Microbiol.* **6,** 1–12 (2015).
20. American Carbon Registry. *Response to Public Comments on Methodology for Compost Additions to Grazed Grasslands*. (2014). at <http://americancarbonregistry.org/carbon-accounting/standards-methodologies/methodology-for-greenhouse-gas-emission-reductions-from-compost-additions-to-grazed-grasslands/compost-grasslands-methodology-response-to-public-comments-final.pdf>
21. American Carbon Registry. *Peer Review Response Document for Methodology for Compost Additions to Grazed Grasslands*. (2014). at <http://americancarbonregistry.org/carbon-accounting/standards-methodologies/methodology-for-greenhouse-gas-emission-reductions-from-compost-additions-to-grazed-grasslands/compost-additions-v1-0-peer-review-document-final.pdf>
22. California Native Plant Society Rare Plant Program. Inventory of Rare and Endangered Plants (online edition, v8-02). (2015).
23. The Nature Conservancy (TNC). *California Rangeland Conservation Coalition Biological Prioritization of Rangelands: Approach and Methods*. (2007).
24. Cameron, D. R., Marty, J. & Holland, R. F. Whither the Rangeland?: Protection and Conversion in California's Rangeland Ecosystems. *PLoS One* **9,** e103468 (2014).
25. Weiss, S. B. Cars , Cows , Deposition Grasslands for Checkerspot Butterflies : Nitrogen Management of Nutrient-Poor a Threatened Species. *Conserv. Biol.* **13,** 1476–1486 (2009).
26. Kroeger, T., Casey, F., Alvarez, P., Cheatum, M. & Tavassoli, L. *An Economic Analysis of the Benefits of Habitat Conservation on California Rangelands. Conservation Economics White Paper.* (2009). at <http://www.defenders.org/programs_and_policy/science_and_economics/conservation_economics/valuation/index.php >
27. Sharpley, A. N. *et al.* Development of phosphorus indices for nutrient management planning strategies in the United States. *J. Soil Water Conserv.* **58,** 137–152 (2003).
28. Haden, V. R., De Gryze, S. & Nelson, N. *American Carbon Registry Methodology for*

Compost Additions to Grazed Grasslands Version 1.0. (2014). at <http://americancarbonregistry.org/carbon-accounting/standards-methodologies/methodology-for-greenhouse-gas-emission-reductions-from-compost-additions-to-grazed-grasslands/compost-additions-to-grazed-grasslands-v1-0_final-1.pdf>

29. Harpole, W. S., Goldstein, L. J. & Aicher, R. J. in *California Grasslands: Ecology and Management* (eds. Stromberg, M. R., Corbin, J. D. & D'Antonio, C. M.) 119–127 (University of California Press, 2007).
30. Fenn, M. E. *et al.* Nitrogen critical loads and management alternatives for N-impacted ecosystems in California. *J. Environ. Manage.* **91,** 2404–2423 (2010).
31. Ochoa-Hueso, R. *et al.* Nitrogen deposition effects on Mediterranean-type ecosystems: An ecological assessment. *Environ. Pollut.* **159,** 2265–2279 (2011).
32. Bobbink, R. *et al.* Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. *Ecol. Appl.* **20,** 30–59 (2010).
33. Pierce, B. L., Redente, E. F., Barbarick, K. a., Brobst, R. B. & Hegeman, P. Plant Biomass and Elemental Changes in Shrubland Forages following Biosolids Application. *J. Environ. Qual.* **27,** 789 (1998).
34. Sullivan, T. S., Stromberger, M. E., Paschke, M. W. & Ippolito, J. A. Long-term impacts of infrequent biosolids applications on chemical and microbial properties of a semi-arid rangeland soil. *Biol. Fertil. Soils* **42,** 258–266 (2006).
35. Kowaljow, E., Mazzarino, M. J., Satti, P. & Jiménez-Rodríguez, C. Organic and inorganic fertilizer effects on a degraded Patagonian rangeland. *Plant Soil* **332,** 135–145 (2010).
36. Pedrol, N. *et al.* Soil fertility and spontaneous revegetation in lignite spoil banks under different amendments. *Soil Tillage Res.* **110,** 134–142 (2010).
37. Stavast, L. J. *et al.* New Mexico Blue Grama Rangeland Response to Dairy Manure Application. *Rangel. Ecol. Manag.* **58,** 423–429 (2005).
38. Martínez, F., Cuevas, G., Calvo, R. & Walter, I. Biowaste effects on soil and native plants in a semiarid ecosystem. *J. Environ. Qual.* **32,** 472–479 (1997).
39. Fresquez, P. R., Francis, R. E. & Dennis, G. L. Soil and vegetation responses to sewage sludge on a degraded semiarid broom snakeweed/blue grama plant community. *J. Range Manag.* **43,** 325–331 (1990).
40. Jurado-Guerra, P., Luna-Luna, M., Flores-Ancira, E. & Saucedo-Teran, R. Residual Effects of Biosolids Application on Forage Production of Semiarid Grassland in Jalisco , Mexico. *Appl. Environ. Soil Sci.* **Article ID,** 5 (2013).
41. Suttle, K. B., Thomsen, M. A. & Power, M. E. Species interactions reverse grassland responses to changing climate. *Science* **315,** 640–642 (2007).

List of participants for the Environmental Farming Act Science Advisory Panel compost subcommittee (expert group)

Kate Scow, PhD (UC Davis)
Whendee Silver, PhD (UC Berkeley)
Dennis Chessman, PhD (USDA Natural Resources Conservation Service)
David Crohn, PhD (UC Riverside)
Peter Green, PhD (UC Davis)
Maria de la Fuente, PhD (UC Cooperative Extension)
Will Horwath, PhD (UC Davis)
Carol Shennan, PhD (UC Santa Cruz)
Doug Parker, PhD (UC Office of the President)
Joji Muramoto, PhD (UC Santa Cruz)
Kelly Gravuer, MSc (California Department of Food and Agriculture)
Amrith Gunasekara, PhD (California Department of Food and Agriculture)
Robert Horowitz (CalRecycle)
Evan Johnson (CalRecycle)
Tung Le (California Air Resources Board)
Sue McConnell (Central Valley Regional Water Quality Control Board)
Brenda Smyth (CalRecycle)
Brian Larimore(CalRecycle)
David Mallory (California Air Resources Board)
Bruce Gwynne (California Department of Conservation)
Scott Couch (State Water Board)
Kyle Pogue (CalRecycle)
Carolyn Cook, MSc (California Department of Food and Agriculture)
Barzin Moradi, PhD (California Department of Food and Agriculture)
Jennifer Kiger (California Air Resources Board)