Modeling Loblolly Pine Aboveground Live Biomass in a Mature Pine-hardwood Stand: A Cautionary Tale

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Abstract

Carbon sequestration in forests is a growing area of interest for researchers and land managers. Calculating the quantity of carbon stored in forest biomass seems to be a straightforward task, but it is highly dependent on the function(s) used to construct the stand. For instance, there are a number of possible equations to predict aboveground live biomass for loblolly pine (*Pinus taeda*) growing in southeastern Arkansas. Depending on stem diameter at breast height (DBH), biomass varied considerably between four different prediction systems for loblolly pine. According to the tested models, individual tree oven-dry biomass for a 50 cm DBH loblolly pine ranged between 1,085 kg and 1,491 kg. Beyond this point, departures between these models became increasingly pronounced, with one even projecting an irrational decline to negative biomass for trees > 138.7 cm DBH, while the others varied between 12,447 and 15,204 kg. Although some deviation is not surprising given the inherent differences in model form and three of the models were extrapolations across much of this diameter range, the difference between the extremes was unexpected. Such disparities significantly impact stand-level (cumulative) predictions of biomass in forests dominated by large-diameter individuals, as demonstrated for an existing stand (Hyatt's Woods) in Drew County, Arkansas. Differences between these models caused loblolly pine aboveground live-tree biomass estimations in Hyatt's Woods to vary by almost 34,000 kg/ha.

Introduction

Loblolly pine (*Pinus taeda*) is probably the most economically important conifer in North America, if not the world (Schultz 1997). Loblolly is found across a wide range of site conditions, grows quickly to large size, has considerable commercial value, can be successfully used in both natural and artificial regeneration systems, and has been well-studied. The productivity of loblolly pine has made it particularly desirable for those looking to maximize woody fiber production in the southeastern U.S. In Arkansas, biomass from forested ecosystems, especially loblolly pine stands, has received increasing attention for its contribution (realized or potential) towards carbon sequestration or bioenergy (e.g., Schuler et al. 2009, Mehmood and Pelkki 2009, Bragg and Guldin 2010).

Most of these studies make a series of assumptions regarding how live-tree biomass is determined. Typically, an allometric equation associating tree diameter at breast height (DBH) and biomass is applied on individual stems, and then summed to yield biomass per unit of land surface area. For commercially important species such as loblolly pine, multiple biomass equations are available. One of the challenges to forecasting tree and stand-level biomass is the accuracy and precision of these models, which leads to a number of relevant questions. Which prediction system yields the most reliable estimates across a range of possible tree sizes? How will differences at the individual stem level translate into real-world conditions at the scale of stands, landscapes, or even regions?

A limited body of research has suggested that there are noticeable differences between biomass equations for loblolly pine in the southeastern U.S. (e.g., Van Lear et al. 1986, Baldwin 1987, Johnsen et al. 2004). Their preliminary assessments are limited to certain forest conditions (in these cases, relatively young loblolly pine plantations) and only suggests of the possibility for departures for other circumstances (for example, mature, pine-dominated stands of natural origin). Furthermore, there may be some fundamental differences in loblolly pine allometry as a function of conditions such as genetics, site quality, and stocking, making it imperative that multiple equations be tested to determine the predictive accuracy for loblolly pine grown in Arkansas. Hence, this study has been designed to evaluate biomass predictions of four different model systems for loblolly pine trees from southern Arkansas.

Table 1. Attributes of the equations tested in this paper, including the DBH range for which the model was derived.

Model reference	Geographic source	Pine stand origin and type	DBH range (cm)
Farrar et al. (1984)	southeast Arkansas	Natural-origin, uneven-aged	9 – 83
Baldwin (1987)	central Louisiana	Planted (even-aged)	5 – 53
Doruska and Patterson	southeast Arkansas	Planted- and natural-origin even-aged	15 – 75
Jenkins et al. (2003)	U.S.-wide	Various origins and age structures	2.5 – 56 [a]

[a] For only the loblolly pine used in their derivations.

Materials and Methods

Research on carbon sequestration almost always involves the quantification of biomass, typically in terms of oven-dry aboveground yield of living trees. Rather than destructively sampling loblolly pines to predict aboveground biomass as a function of diameter at breast height (DBH), four existing allometric models were adapted for this purpose (Table 1). Some of these models were initially designed to predict sawtimber (wood only) or merchantable bole volumes (including wood and bark), not total aboveground biomass, and thus had to be adapted to produce the desired output. All stem volume model predictions were converted to cubic meters, then multiplied by the oven-dry weight of loblolly pine (in kg/m^3) to yield aboveground stem biomass for a loblolly pine of the given DBH. Models that predicted bole biomass only were also converted to total tree biomass using factors based on tree size.

Three of these models were derived from naturally or artificially regenerated loblolly pine stands in Arkansas and Louisiana. The first example used a set of polynomial equations to predict the growth and yield of uneven-aged pine stands on or near the Crossett Experimental Forest in Ashley County, Arkansas (Farrar et al. 1984). Of these, the equation that predicted merchantable wood volume (V_M) to an 8.9 cm top was used:

$$V_M = \left[-1.41726 - 0.02484\left(\frac{DBH}{2.54}\right) + 0.09948\left(\frac{DBH}{2.54}\right)^2 + 0.00748\left(\frac{DBH}{2.54}\right)^3 - 0.00017\left(\frac{DBH}{2.54}\right)^4\right] \times 0.02832 \quad (1)$$

An additional adjustment to produce total loblolly pine bole biomass was needed. Clark and Saucier (1990) estimated a nonlinear ratio (Y_R, where $0.0 < Y_R \leq 1.0$) between these volumes:

$$Y_R = e^{-2.45015(d^{4.64713} DBH^{-4.81445})} \quad (2)$$

where d is the upper (stem-top) tree diameter (for this study, fixed at 8.3 cm). Thus, total bole wood volume (V_T) follows:

$$V_T = V_M / Y_R \quad (3)$$

According to the work of Patterson et al. (2004), one cubic meter of green (100% moisture content) loblolly pine wood from southeastern Arkansas averages 1,025 kg and weighs 50% less (512.5 kg) when oven-dry. Thus, oven-dry bole biomass (b_D) was determined by multiplying the volume (V_T) by its green weight per unit volume, then halving that quantity, i.e., $b_D = b_G \times 0.5$. All final biomass values are oven-dry weights.

The second model system was developed from field data collected in a log weight scale study in southern Arkansas (Posey et al. 2005, Doruska and Patterson 2006). For pulpwood-sized (stems < 25 cm DBH) loblolly pines, the following equation was used:

$$b_G = \left[-26.23697 + 0.1431\left(\left(\frac{DBH}{2.54}\right)^2 \times \left(\frac{H}{0.3048}\right)\right) + 0.00481\left(\left(\frac{DBH}{2.54}\right)^2 \times \left(\frac{H}{0.3048}\right)\right)\right] / 2.2 \quad (4)$$

where b_G equals green bole biomass to a 7.6-cm diameter top and H is total tree height. Sawtimber-sized loblolly pine bole biomass was calculated somewhat differently:

$$b_G = \left[e^{-0.1341 + 2.0178\left(ln\left(\frac{DBH}{2.54}\right)\right) + 0.5726\left(ln\left(\frac{H}{0.3048}\right)\right)}\right] / 2.2 \quad (5)$$

Equations (4) and (5) also require height, so a model developed for loblolly pine in southeastern Arkansas was used to predict total tree height from DBH (Bragg 2008):

$$H = 1.37 + 41.9641(1 - e^{-0.0247DBH})^{1.1496} \quad (6)$$

Equations (4) and (5) were then converted to b_D.

The third bole biomass equation was developed by Baldwin (1987) for loblolly pine plantations in central

Table 2. Species composition and stand density of Hyatt's Woods in Drew County, Arkansas, measured in 2009.

Species	Trees per ha	Basal area (m^2/ha)
Baldcypress (*Taxodium distichum*)	5.8	3.6
Loblolly pine (*Pinus taeda*)	54.6	15.7
Red maple (*Acer rubrum*)	2.5	0.2
American hornbeam (*Carpinus caroliniana*)	19.0	0.2
Water hickory (*Carya aquatica*)	7.4	0.4
Bitternut hickory (*Carya cordiformis*)	0.8	0.3
Black hickory (*Carya texana*)	2.5	0.2
Mockernut hickory (*Carya tomentosa*)	32.2	2.0
Flowering dogwood (*Cornus florida*)	1.7	0.0
Common persimmon (*Diospyros virginiana*)	2.5	0.1
Green ash (*Fraxinus pennsylvanica*)	3.3	0.2
American holly (*Ilex opaca*)	3.3	0.1
Sweetgum (*Liquidambar styraciflua*)	23.1	2.5
Red mulberry (*Morus rubra*)	0.8	0.1
Blackgum (*Nyssa sylvatica*)	11.6	0.8
Eastern hophornbeam (*Ostrya virginiana*)	38.0	0.5
Black cherry (*Prunus serotina*)	1.7	0.0
White oak (*Quercus alba*)	20.7	4.4
Cherrybark oak (*Quercus pagoda*)	18.2	1.4
Swamp chestnut oak (*Quercus michauxii*)	3.3	0.9
Water oak (*Quercus nigra*)	3.3	0.2
Willow oak (*Quercus phellos*)	1.7	0.2
Shumard oak (*Quercus shumardii*)	9.1	1.0
Post oak (*Quercus stellata*)	2.5	0.5
Sassafras (*Sassafras albidum*)	4.1	0.2
Winged elm (*Ulmus alata*)	60.3	1.4
Totals =	333.9	37.1

Louisiana. Baldwin's exponential model also included an age (A) component:

$$b_D = e^{-3.31353+1.91029(ln(DBH))+1.19118(ln(H))+0.000076A^2} \quad (7)$$

Since there was no age data for any of the trees simulated, a DBH-age relationship was adapted from data collected on an uneven-aged loblolly pine-dominated stand on the Crossett Experimental Forest:

$$A = 9.5088DBH^{0.6244} \quad (8)$$

Although the relationship between age and diameter is fairly weak in uneven-aged stands, this particular nonlinear function accounted for approximately 87% of the variance in the 125 tree data set used to derive it (D.C. Bragg, unpublished data). Absent better age data, equation (8) should suffice for the purposes of this work (especially given the limited impact of tree age on biomass using Baldwin's model).

Additionally, for all of these bole biomass-only models it was necessary to use softwood-only scalars (from Jenkins et al. 2003) to produce total above-ground tree biomass (= foliage biomass + branch biomass + bole bark biomass + bole wood biomass). The general form of these scalars follows:

$$\varphi_i = e^{\beta_0+\frac{\beta_1}{DBH}} \quad (9)$$

Where β_i are component-specific parameters and φ_i is a ratio (between 0.0 and 1.0) for one of four possible aboveground components: foliage, branches, bole bark, and bole wood (all of these sum to 1.0, or $\varphi = \Sigma\varphi_i = 1.0$). Hence, aboveground total biomass (in oven-dry terms) is the product of the sum of the components from equation (9) and model's specific biomass estimates, or $B_D = b_D \times \varphi$. For the Farrar et al. model, this ratio scalar incorporated foliage, bark, and branches, while the Doruska and Patterson and Baldwin models used only foliage and branches (both bole bark and stem wood were included in their bole biomass estimates).

The final model used for this analysis was the National Biomass Estimator by Jenkins et al. (2003). Their model directly predicts total aboveground tree oven-dry biomass (in kg):

$$B_D = e^{-2.5356+2.4349(ln(DBH))} \tag{10}$$

Unlike the first three systems, the Jenkins et al. (2003) approach was developed from an amalgamation of "pseudodata" generated using 43 different equations from 14 different pine species. Of these equations, only four were loblolly pine. Hence, the Jenkins et al. (2003) pine is the least "pure" set of information, although all of the models had some issue with their applicability. For example, equation (1) was calculated for a specific merchantable top diameter, and thus had to use equations (2) and (3) to correct for the "missing" biomass (the rest of the bole). Baldwin's study was for planted loblolly pine in central Louisiana (Baldwin 1987), and the Doruska and Patterson data included both planted and naturally regenerated loblolly (Doruska and Patterson 2006). The Jenkins et al. model used pines up to 180 cm in DBH, although none of their data sets included loblolly pine > 56 cm DBH (Jenkins et al. 2004). The other three loblolly pine-only equations incorporated stems between 5 and 83 cm (Table 1).

Thus, none of these models are "ideal" for calculating total aboveground tree biomass for large diameter loblolly pines in southern Arkansas. This work is not intended as a criticism of the original models, but rather to highlight how their predictions, when extrapolated beyond the range of data, will produce results that can differ substantially, even when other aspects are held constant.

To help evaluate differences in biomass projections as a function of model, a mature, unmanaged stand (Hyatt's Woods) in southern Drew County, Arkansas, was used as an example. In composition, landform position, and management history, Hyatt's Woods is comparable to many other naturally regenerated stands in this part of Arkansas. This 1.2-ha stand, located along a stream terrace of Brown's Creek, is primarily hardwood but has a prominent (42% of total stand basal area) loblolly pine component in the overstory (Table 2). A stand table comprised of loblolly pine counts per hectare by 10 cm DBH class was entered into a spreadsheet. Biomass volumes for trees of a specified diameter class midpoint were calculated using each of the four models in this study, multiplied by the number of pines in each size class, and then summed across all size classes to approximate the total aboveground live-tree, oven-dry loblolly pine biomass for this stand.

Results and Discussion

Small to moderate diameter loblolly pine predictions

Figure 1 shows similarity in both the shape and magnitude of the curves up to 50 cm DBH. Across this range, three of the models (Farrar et al., Doruska and Patterson, Baldwin) rarely differed by more than 20-25% from their central tendency, and in most instances were within 10%. Generally, this low variability should fall within the range expected for biomass estimates, suggesting that very little difference in performance can be detected between these models to 50 cm DBH. According to Rosson (2002), approximately 99% of the estimated 533 million loblolly pine growing in the state of Arkansas were less than 50 cm in DBH, a fraction that will almost certainly have increased as mature trees have continued to be harvested or died and are replaced by small diameter stems. Hence, efforts to predict aboveground carbon storage in a "typical" Arkansas loblolly pine should be adequately satisfied by most if not all of the equations used in this paper.

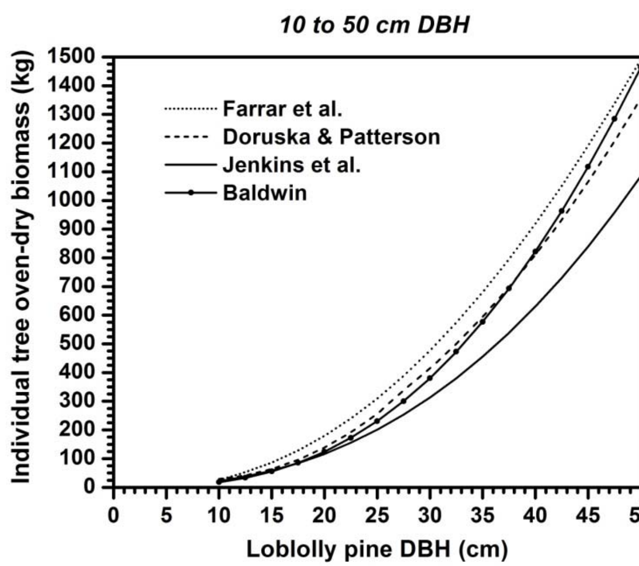

Figure 1. Predicted aboveground live-tree, oven-dry biomass as a function of stem diameter for loblolly pines between 10 and 50 cm DBH using the four different model systems.

However, the biomass equation of Jenkins et al. (2003) produced appreciably different biomass predictions, as much as 24-27% lower than the average of the other models across most of the 10-50 cm DBH range. Presumably, this disparity is largely a function of the generality of the derivation of the Jenkins et al. model, which included *Pinus* of a number of different species, many of which have substantially less dense oven-dry wood than *Pinus taeda* (Miles and Smith 2009).

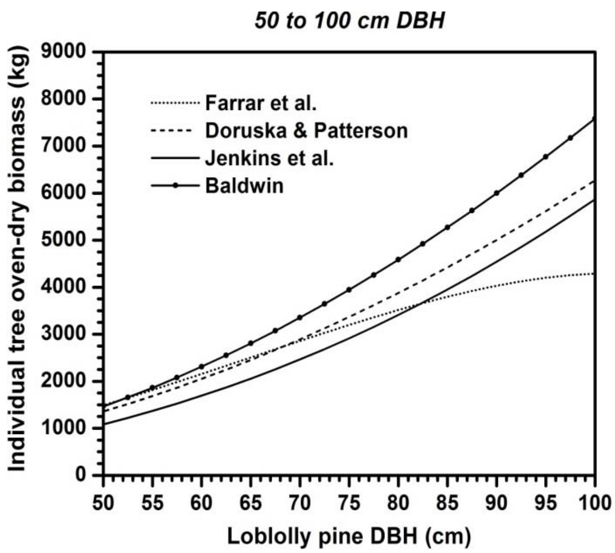

Figure 2. Predicted aboveground live-tree, oven-dry biomass as a function of stem diameter for loblolly pines between 50 and 100 cm DBH using the four different model systems.

Large tree predictions

Loblolly pine aboveground biomass predictions begin departing soon after the stems reach 50 cm DBH, with the differences becoming increasingly pronounced as the pines get larger. Even though the general shape of the Doruska and Patterson, Baldwin, and Jenkins et al. curves are similar (Figure 2), their rates of increase differ and hence their predictions are not proportionally similar. For instance, the Doruska and Patterson and Baldwin predictions for a 50 cm DBH pine differed by only 108 kg (about 8%), compared to an almost 19% mean difference at 100 cm DBH (Table 3). The Jenkins et al. predictions are approximately proportionate for loblolly pines from 50 to 100 cm DBH as they were from 10 to 50 cm DBH, with the exception of the Farrar et al. equation, which has started a prominent departure.

Unlike the others, the Farrar et al. model peaks at about 102 cm DBH, and then begins to rapidly drop until it reaches zero biomass at just under 139 cm DBH (Figure 3, Table 3). Needless to say, it is physically impossible for a loblolly pine of this size to have no biomass. This result arises because the polynomial function used is extrapolated well beyond the range of its original data. Such a disparity was inevitable, given the negative coefficient of the biquadrate of equation (1), which causes a systematic decrease in individual tree biomass as DBH increases. The other models use monotonically increasing power or exponential functions, and thus will never predict such a decline—at just under 139 cm DBH, they yielded estimates between 13,023 and 17,928 kg.

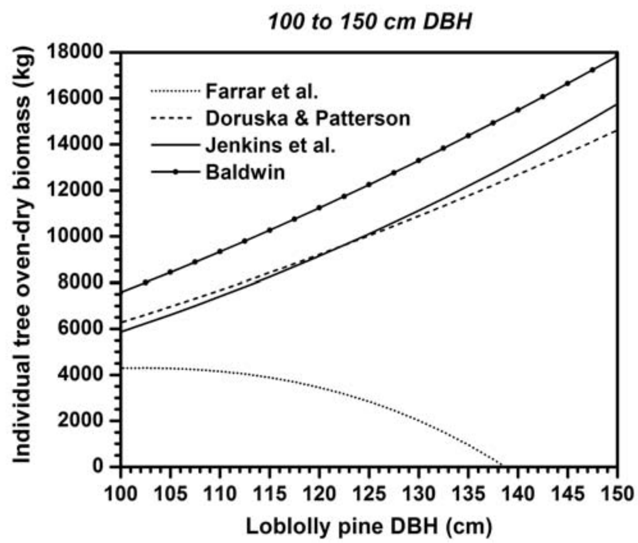

Figure 3. Predicted aboveground live-tree, oven-dry biomass as a function of stem diameter for loblolly pines between 100 and 150 cm DBH using the four different model systems. Note the dramatic departure of the Farrar et al. system from the others.

For the largest of loblolly pines (Figure 3), the three most reasonable models continue to increase in their biomass predictions. The Baldwin equation retains its position as the highest predictor of biomass. At just under 125 cm, the Doruska and Patterson and Jenkins et al. models switch order, but otherwise remain similar. Without destructively sampling very large live trees, it is not possible to say which model system is most appropriate at this extreme in the diameter range for southern Arkansas loblolly. Even though the Baldwin and Doruska and Patterson models were regionally derived from loblolly pine stands, they only included specimens of fairly limited dimensions and were thus not necessarily more reliable across all size classes than the Jenkins et al. model, which used considerably larger trees (but not of loblolly pine). This exemplifies the challenge of this type of effort, when models capable of predicting very large tree biomass are needed but do not currently exist.

Table 3. Aboveground live-tree, oven-dry biomass as a function of individual tree size and model system for loblolly pine growing in southern Arkansas. Italics denote predictions of tree biomass beyond the original model DBH range.

	Predicted quantity (in kg)			
DBH (cm)	Farrar et al.	Doruska and Patterson	Baldwin	Jenkins et al.
10	25	29	18	22
25	309	256	231	201
50	1491	1356	1464	1085
75	3196	3365	*3946*	*2913*
100	*4292*	*6271*	*7586*	*5870*
125	*2839*	*10031*	*12247*	*10106*
137.5	*330*	*12222*	*14930*	*12746*
150	*-3908*	*14617*	*17835*	*15753*

Implications for larger scale modeling

The appropriateness of model form under all possible size classes is an important issue. For this type of biomass work, it is advisable for researchers to project their models to the very upper end of the species potential to ensure that irrational results do not occur. The allometric behavior of trees across the range of potential sizes should be one of several criteria used to determine the utility of a modeling system. After all, models developed with limited sample size, restricted geographic distributions, or abbreviated portions of the possible dimensional range are susceptible to influence by outliers or the central tendency of only a portion of the possible conditions. For instance, even though the Farrar et al. model was derived with pines up to 83 cm in DBH, only a few large specimens were used, thus allowing the bulk of the data (smaller trees) to determine the response curve. Hence, when coupled with the polynomial function, irrational large tree predictions were inevitable.

This particular example serves as a cautionary tale for researchers projecting live tree biomass over long time spans, especially as the trees age and approach their upper dimensional limits. Those wishing to project beyond the range of the functions may experience unexpected outcomes. However, such extrapolation may be unavoidable—even though only a fraction of loblolly pines today exceed 100 cm in DBH, it can grow to this size. For instance, a former national champion loblolly near Warren, Arkansas, had a DBH of 152 cm, and historical records from the region exceed even this, with pines from Ashley County, Arkansas, reportedly greater than 180 cm in diameter (Bragg 2002).

Table 4. Stand-level loblolly pine-only aboveground live-tree, oven-dry biomass for Hyatt's Woods predicted by the different modeling approaches. Italics denote predictions of tree biomass beyond the original model DBH range.

DBH class midpoint (cm)	Live pine stocking (stems/ha)	Farrar et al. (1984) (kg/ha)	Doruska and Patterson (kg/ha)	Baldwin (1987) (kg/ha)	Jenkins et al. (2003) (kg/ha)
5	0	0	0	0	0
15	1	72	53	46	48
25	1	257	213	192	167
35	1	565	493	479	378
45	10	11814	10563	11086	8331
55	15	27008	25060	27696	20371
65	19	47637	46607	*53350*	*39088*
75	6	18506	19486	*22847*	*16868*
85	2	9419	*10968*	*13072*	*9799*
TOTALS:	55	115278	113442	128768	95051

The simulation of the loblolly pine component at Hyatt's Woods further demonstrates the sensitivity of the biomass predictions to the model used. In this mature pine-dominated unmanaged stand, few small diameter loblolly are present, and the big pines (those 65 cm DBH or greater) dominate the biomass contributions (Table 4). The Farrar et al. model system predicted the loblolly pine component of this stand to have just over 115,000 kg/ha of biomass, compared to 113,442 kg/ha using the Doruska and Patterson models, 128,768 kg/ha from the Baldwin model, and 95,051 kg/ha according to Jenkins et al.

Thus, stand-level disparities of almost 34,000 kg/ha appear in this one limited example, suggesting that considerable variation in aboveground biomass due solely to model choice can be expected. While these equations are used beyond their range of original data, it is commonplace for biomass estimation to use extrapolated models without consideration of the reliability of these estimates. This is particularly true when simulations are expanded regionally or over long time frames (e.g., Birdsey et al. 2006), and calls into question large-scale carbon storage estimates based on equations that have not been properly evaluated.

Conclusions

A test of a handful of different biomass prediction systems shows that model choice definitely influences estimates of aboveground biomass in loblolly pine. This comparison strongly suggests that researchers examine the full range of potential tree size when evaluating which model system to apply given a number of alternatives. As suggested by a real-world example from Hyatt's Woods, aboveground biomass estimates can arise that may differ by as much as one-third in mature stands of loblolly pine-dominated forest solely based on the model used. In an era of increasing environmental and economic interest in carbon sequestration, the question of appropriate model selection has yet to be adequately addressed.

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