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An Optimization-Based System Model of Disturbance-Generated Forest Biomass Utilization

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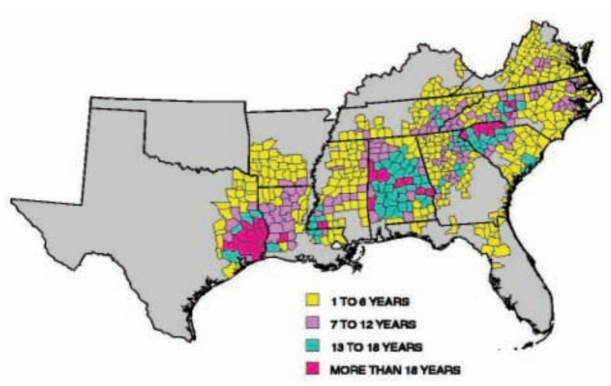
Disturbance-generated biomass results from endogenous and exogenous natural and cultural disturbances that affect the health and productivity of forest ecosystems. These disturbances can create large quantities of plant biomass on predictable cycles. A systems analysis model has been developed to quantify aspects of system capacities (harvest, transportation, and processing), spatial aspects of the biomass generation process, and deterioration impacts on biomass quality in the various inventory states (field stands, field-harvested inventories, transportation prepared inventories, and production facility inventories). Optimal decision alternatives can be used to guide responses to reclamation, utilization, mitigation, and control. This is particularly advantageous in insect and disease outbreaks, in which the process may last several years, with varying levels of intensity. The prescriptive system description, assuming capacities are fixed, results in a linear programming model. The time-dependent capacity decision model results in a mixed-integer programming model. The analytical model is developed in detail in this analysis.

Keywords: *systems analysis; linear programming; disturbance generated; biomass utilization*

By *disturbance-generated biomass*, we mean specifically the quantity of plant biomass resulting from endogenous and exogenous natural and cultural disturbances that normally affect the conditions of forest ecosystems. Examples of disturbances that create large quantities of plant biomass on predictable cycles include insect and disease outbreaks, hurricanes, forest fires, ice storms, wind storms, and so on. Each type of disturbance has a set of specific characteristics (mode of action, organization level, scale, duration, severity, timing, frequency, and reliability or predictability) that affect the quantity and quality of plant biomass that is generated. Typically, when a disturbance occurs, local wood product markets become swamped, and traditional utilization pathways (e.g., saw logs, pulpwood) close because of a lack of demand. Consequently, the resource is abandoned, and the economic value of the commodity is lost. The annual quantity of disturbance-generated plant biomass from all sources is substantial, and the practicality of utilization through a variety of pathways can be evaluated using operation research engineering tools and econometric procedures. Methodologies for ecological impact assessment are also well developed. The ecological and economic impact of disturbance-generated plant biomass in forested regions of the southern United States has not been assessed from a utilization perspective (Coulson & Stephen, 2006).

Authors' Note: The research reported herein is part of a project in the Knowledge Engineering Laboratory (KEL; http://kelab.tamu.edu) at Texas A&M University. KEL research deals in part with the development and delivery of integrated computer-based systems for planning, problem solving, and decision support. Evaluating the utilization of southern pine beetle–generated plant biomass involves different kinds of subject-domain expertise.

Figure 1
The Number of Years in Which the Southern Pine Beetle Reached Outbreak Status Since 1960



Source: U.S. Forest Service (1995).

The goal of the associated research project is to evaluate the utilization of disturbance-generated plant biomass. The four specific objectives are (a) to develop a model to evaluate utilization pathways for disturbance-generated plant biomass; (b) to define the spatial and temporal distribution, type, and quantity of disturbance-generated plant biomass in the South; (b) to evaluate the economic feasibility of the various utilization pathways of disturbance-generated plant biomass; and (d) to evaluate the ecological consequences of the utilization of disturbance-generated plant biomass. Emphasis has been placed on plant biomass generated by hurricanes and outbreaks of the southern pine beetle (SPB) because of the recurrent and catastrophic effects these disturbances have on rural and urban forestlands in the southern United States. In this article, we define the pathways utilization problem and propose a model based on linear programming for the prescriptive evaluation of how best to utilize a standing system in which capacities are not part of the decision process.

Background

Outbreaks of the SPB, *Dendroctonus frontalis*, and hurricanes are fundamental components of the natural disturbance regime of the South. These disturbances are recurrent, and they create a large quantity of plant biomass that is wasted because the supply is greater than traditional market demand. In addition, the quality of the plant biomass available degrades with time, and it is often not suitable for processing into finished wood products. These facts are well recognized but have not been addressed with a plan that includes alternative utilization pathways (Gan, 2004).

The SPB is the most significant biotic mortality agent affecting yellow pines in the South. Figure 1 summarizes succinctly the magnitude of SPB's impact in the South. Outbreaks of the SPB vary in their intensity and duration and cycle within the South. Efforts directed to the suppression and prevention of SPB outbreaks generate substantial quantities of plant biomass (Table 1) (Coulson et al., 2004).

Hurricanes occur annually (often with multiple episodes) in the South, and their impact on urban and rural forests varies greatly as a function of the frequency, intensity, and duration of the disturbance events (Chouinard & Liu 1997). Unlike SPB outbreaks, in which the disturbance-created plant biomass is generated over a 2- to 4-year period, the impact of hurricanes is immediate and broadly distributed (Figure 2) (Texas Forest Service, 2005; U.S. Forest Service, 2006).

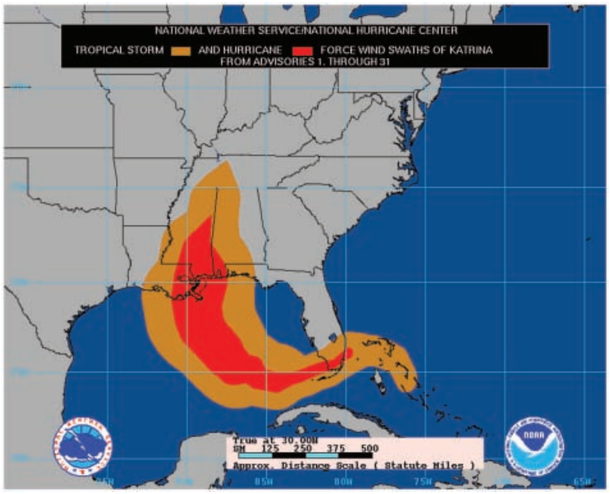
The quantity of hurricane-generated plant biomass from forestlands greatly exceeds any local market demands. The quality rapidly deteriorates, and alternatives for utilization beyond milling and pulping have not been examined in an economic context. Hurricanes, in addition to their impact on urban and rural forests, also create substantial quantities of woody debris that cannot be processed using traditional manufacturing practices for forest products. Alternative uses for this debris have not been evaluated (Richardson, Björheden, Hakkila,

Table 1
Total Economic Losses and Social Impact (in U.S. dollars) Resulting From Outbreaks of the Southern Pine Beetle on Three National Forests in the Southern United States

National Forest	Time Period	Sawtimber Losses	Pulpwood Losses	Economic Impact	Social Impact
Homochitto (Mississippi)	1986 to 2001	$8,947,618	$376,268	$9,323,887	$2,330,971
Kitsatche (Louisiana)	1989 to 2001	$101,460	$10,923	$112,382	$28,095
Bankhead (Alabama)	1986 to 2001	$19,966,839	$584,569	$20,545,198	$5,136,299

Source: From a study conducted by the Knowledge Engineering Laboratory for the U.S. Forest Service, Forest Health Protection.

Figure 2
Path of Hurricane Katrina (2005), Defined by the Intensity of Winds



Source: National Hurricane Center (2005).

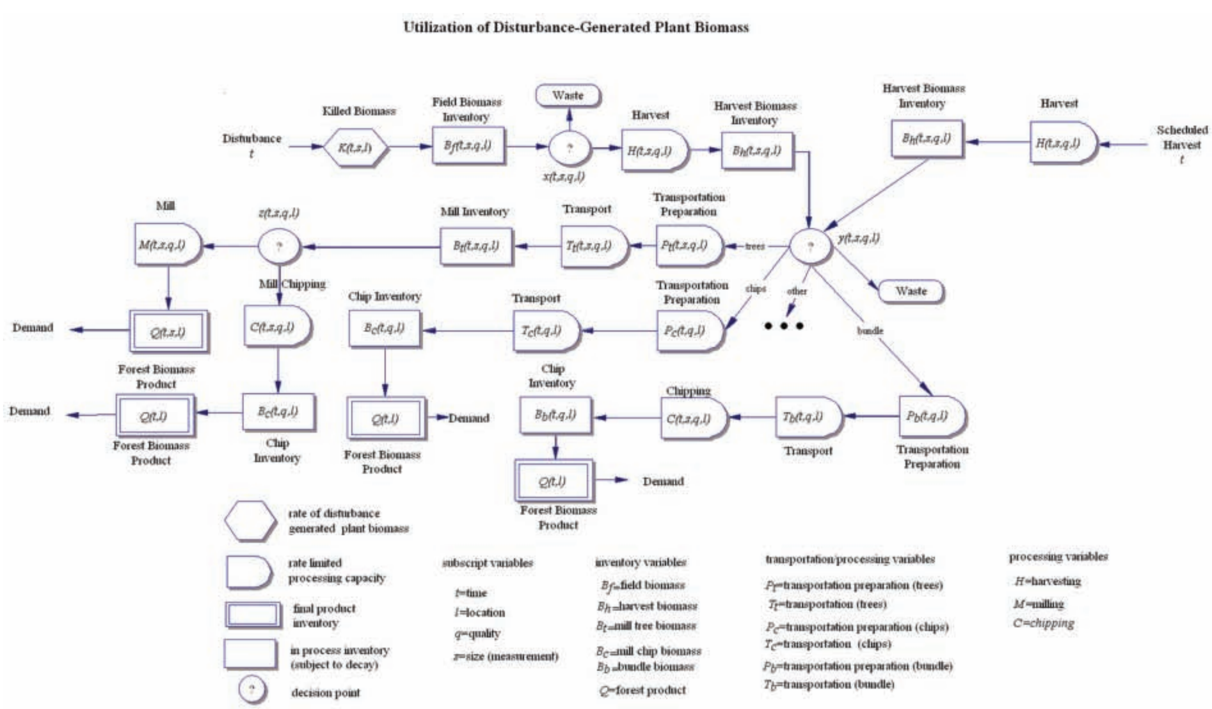
Note: The depth and breadth of the winds of hurricane and tropical storm force affected substantial portions of five southern states.

Lowe, & Smith, 2003; Richardson, Björheden, Popescu, & Smith, 2004).

Technical Approach

The model depicted in Figure 3 deals with utilization pathways for disturbance-generated plant biomass. The model incorporates variables such as the flow (quantity) of biomass, the quality of biomass (e.g., deterioration over time), harvesting practices, transportation options, rate-limited processing capacity, and end-product demand (e.g., lumber, pulp, bioenergy, other biologically based products). Key features of the utilization process captured by the model include the following: (a) The plant biomass can originate either from a disturbance event, such as an SPB outbreak or a hurricane, or as a scheduled forestry practice, such as a sanitation cut; (b) different harvesting practices are possible, and there are costs and benefits associated with each; (c) the harvested product can be transported in several forms (e.g., trees, chips, bundles), and again, there are costs and benefits associated with each; (d) the rate of plant

Figure 3
General Flow Model for the Utilization of Southern Pine Beetle–Generated Plant Biomass



Source: Coulson et al. (n.d.).

biomass decomposition influences utilization options; and (5) plant biomass can be used for a variety purposes (such as heat, electricity, and transportation fuels).

Optimization Model

The following model is a linear program (see Bazaraa, Jarvis, & Sherali, 1980, for an in-depth discussion of linear programming and associated solution algorithms) that will find the optimal profit (revenue minus costs) for a system including harvesting decisions over time, age category, and size. The profit entity can be either the total system cost from harvest to milling or the harvest and delivery subsystem. The model is based on a scenario involving multiple time periods, with inputs of the number of units of biomass killed per period t and size category r, $K(t,r)$. The formulation includes initial inventories of all inventoried items in the formulation. A basic assumption for this model is that the modeling time period is long enough that trees could be killed, harvested, transported, and processed into chips and/or lumber during a single period (such as 1 month). Note that this specific model also has only the two most basic transportation modes: logs and chips. Several capacities are assumed in the model, such as the harvest capacity of biomass for logs and of biomass for chips for each time period, $C^{HL}(t)$ and $C^{HC}(t)$. All of the capacities can change with time period t, but they are assumed known and thus are external inputs. For the sake of space and simplicity, we present a single-region model. Various production options are taken into account in the model. For example, the usable log fraction of a tree is defined by the parameter α (<1.0), and the complement of the biomass of these trees $(1 - \alpha)$ can be left in the field or harvested for chip production. To allow this production choice to be a user input, the parameter μ is used as a model input. If $\mu = 1$, the log-harvest waste biomass is collected and chipped, and if $\mu = 0$, this biomass is left in the field. Several model parameters are specified by the modeler. These are as follows:

- α (<1.0) = the average fraction of a tree that can be used for logs (approximately 65%)
- β (<1.0) = the average fraction of a log that yields usable lumber (approximately 75%)
- μ (1 or 0) = a log-harvesting policy in which biomass waste is used in chip production ($\mu = 1$)

The approach taken to represent inventories at the beginning of the analysis period ($t = 0$) is based on the concept that all inventories herein are modeled as ending-period values. Hence, initial inventories are the ending inventories for the period $t = -1$, and these become the starting inventories for period $t = 0$. But we denote these in the same fashion as they are indexed within the model: as ending inventories for the previous period ($t = -1$). Thus, when a model inventory variable of the form $I^X(t,s,r)$ is encountered, the initial inventory values for that set of variables are assumed given and are denoted $I^X(-1,s,r)$. Throughout the model, t refers to time, s refers to the age of the biomass since it was killed for quality deterioration accuracy, and r refers to the diameter at breast height (DBH) category. All inventory variables start with an uppercase I for ease of reading the model. It is also assumed that there is a parameter, L, that indicates the maximum age (in model time periods) for the value of the index s at which dead biomass is still viable. To reiterate, initial inventories are not system variables. They are known-quantities values. For ease of modeling, these known values have been denoted the same as the associated variable names, except that when used with the time index value of $t = -1$, these are then recognized as known initial values, not actually system variables. This formalism allows a more concise model formulation and generally reduces by one third the number of explicit equations needed to represent a given case being modeled.

Model Variables

The model variables are listed below.

Variable Definitions

$H_L(t,s,r)$ = harvested log biomass at time t of age s and size r,

$H_C(t,s,r)$ = harvested chip biomass at time t of age s and size r,

$C_{HC}(t,s,r)$ = chips from harvested biomass for that purpose at time t of age s and size r,

$C_{LW}(t,s,r)$ = chips from log transportation preparation waste at time t of age s and size r,

$T_L(t,s,r)$ = transported biomass in log form at time t of age s and size r,

$T_{CM}(t,s)$ = transported biomass chips to mills at time t and of age s,

$T_{CE}(t,s)$ = transported biomass chips to energy sites at time t and of age s,

$P_L(t, s, r)$ = production of timber from logs at time t of age s and size r,

$P_C^{LW}(t, s, r)$ = production of chips from log milling waste at time t of age s and size r,

$P_C^L(t, s, r)$ = mill production of chips directly from logs at time t of age s and size r,

$P_P^{MC}(t, s)$ = mill processing of chips of age s for pulpwood,

$P_E^{MC}(t, s)$ = mill processing of chips of age s for energy,

$P_E^{oC}(t, s)$ = chips used for energy at other sites o at time t of age s,

End-of-Period Inventories

$I^K(t, s, r)$ = field inventory of killed biomass at time t of age s and size r,

$I^{HC}(t, s, r)$ = inventory of harvested biomass for chips at time t of age s and size r,

$I^{LW}(t, s, r)$ = inventory of waste biomass from log transportation preparation at time t of age s and size r,

$I^{CF}(t, s)$ = field inventory of chip biomass at time t of age s,

$I^L(t, s, r)$ = inventory of log biomass at the mills at time t of age s and size r,

$I^{PW}(t, s, r)$ = inventory of log production waste at the mills at time t of age s and size r,

$I_M^C(t, s)$ = inventory of chips produced at the mills at time t of age s,

$I_E^{oC}(t, s)$ = inventory of chips at energy sites o at time t of age s,

Capacities

$C_L^H(t)$ = log biomass harvesting capacity at time t,

$C_C^H(t)$ = chip biomass harvesting capacity at time t,

$C_{LC}^H(t)$ = total biomass harvesting capacity at time t,

$C_C^P(t)$ = capacity of chip production at time t,

$C_L^T(t)$ = capacity of log preparation and transportation at time t,

$C_C^T(t)$ = capacity of chip transportation at time t,

$C_{LC}^T(t)$ = capacity of total log and chip transportation at time t,

$C_L^M(t)$ = capacity of log processing at the mills at time t,

$C_C^M(t)$ = capacity of chip production at the mills at time t,

$C_P^M(t)$ = capacity processing chips at the mills at time t,

$C_E^M(t)$ = capacity of energy production from chips at the mills at time t,

$C_E^o(t)$ = capacity of energy production from chips at other sites at time t,

Revenue Values

$v_P(t,s)$ = the revenue / ton at time t of pulpwood of age s (mill point of view),

$v_T(t,s,r)$ = the revenue / ton at time t of timber of age s and size r (mill point of view),

$v_E(t,s)$ = the revenue / ton from energy at time t from chips of age s (mill and energy sources point of view),

$v_C(t,s,r)$ = the revenue / ton at time t of chips at mill of age s (harvester point of view),

$v_L(t,s,r)$ = the revenue / ton at time t of logs at mill of age s and size r (harvester point of view),

Costs

$c_{SP}(t)$ = stumpage cost of pulpwood and energy biomass at time t,

$c_{ST}(t,r)$ = stumpage cost of saw timber biomass at time t of size r,

$c_H(t,r)$ = harvesting cost at time t of biomass of size category r,

$c_L^T(t,r)$ = cost of preparation and transportation cost / ton for log biomass at time t of size category r,

$c_C(t)$ = chipping cost / ton at time t,

$c_C^{TM}(t)$ = cost / ton for transportation of chips biomass to mill locations at time t,

$c_C^{To}(t)$ = cost / ton for transportation of chips biomass to energy locations at time t,

$c_C^P(t)$ = chipping cost / ton from logs and timber production waste at the mills at time t.

The linear programming model is as follows (in the notation, $\wedge$ = minimum):

maximize $Return = \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} v_T(t,s,r) P_L(t,s,r)$

$+ \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} v_E(t,s) \left[P_E^{MC}(t,s) + P_E^{oC}(t,s,r) \right]$

$+ \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} v_P(t,s) P_P^{MC}(t,s)$

$+ \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \left[v_C(t,s) - C_C^{TM}(t) \right] T_{CM}(t,s)$

$+ \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \left[v_C(t,s) - C_C^{To}(t) \right] T_{CE}(t,s)$

$+ \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} \left[v_L(t,s,r) - C_L^{T}(t,r) \right] T_L(t,s,r)$

$- \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} C_C(t,r) \left[C_{HC}(t,s,r) + C_{LW}(t,s,r) \right]$

$- \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} C_C^{P}(t,r) \left[P_C^{LW}(t,s,r) + P_C^{L}(t,s,r) \right]$

$- \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} \left[C_H(t,r) + C_{ST}(t,r) \right] H_L(t,s,r)$

$- \sum_{t=0}^{T} \sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} \left[C_H(t,r) + C_{SP}(t,r) \right] H_C(t,s,r)$

The model is subject to the following restrictions.

Harvesting Restrictions ($t = 0, \dots, T$)

(1) $\sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} H_L(t,s,r) \le C_L^H(t)$, (independent harvesting capacity)

(2) $\sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} H_C(t,s,r) \le C_C^H(t)$, (independent harvesting capacity)

(3) $\sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} \left[H_L(t,s,r) + H_C(t,s,r) \right] \le C_{LC}^H(t)$, (joint harvesting capacity)

(4) $\sum_{s=t} \left[H_L(s,s-t,r) + H_C(s,s-t,r) \right] \le K(t,r)$, for $r = 1, \dots, R$,

Harvesting Restrictions Using Initial Inventories

(5) $\sum_{t=0} \left[H_L(t,t+s,r) + H_C(t,t+s,r) \right] \le I^K(-1, s-1, r)$, for $s = 1, \dots, L$, and $r = 1, \dots, R$,

Transportation of Logs ($t = 0, \dots, T$)

(6) $T_L(t,0,r) \le \alpha H_L((t,0,r)$, for $r = 1, \dots, R$,

(7) $T_L(t,s,r) \le \alpha \left[H_L((t,s,r) + I^{HL}(t-1, s-1, r) \right]$, for $s = 1, \dots, L-1$, and $r = 1, \dots, R$,

(8) $\sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} T_L(t,s,r) \le C_L^T(t)$,

Chips From Log Transportation Waste ($t = 0, \dots, T$)

(9) $C_{LW}(t,0,r) \le \mu \frac{1-\alpha}{\alpha} T_L(t,0,r)$, for $r = 1, \dots, R$,

(10) $C_{LW}(t,s,r) \le \mu \frac{1-\alpha}{\alpha} T_L(t,s,r) + I^{LW}(t-1, s-1, r)$, for $s = 1, \dots, L-1$, $r = 1, \dots, R$,

Chips From Harvested Chips Biomass ($t = 0, \dots, T$)

(11) $C_{HC}(t,0,r) \le H_C(t,0,r)$, $r = 1, \dots, R$,

(12) $C_{HC}(t,s,r) \le H_C(t,s,r) + I^{HC}(t-1, s-1, r)]$, for $s = 1, \dots, L-1$, $r = 1, \dots, R$,

Chipping Capacity Limitations ($t = 0, \dots, T$)

(13) $\sum_{s=0}^{t\wedge L} \sum_{r=1}^{R} \left[C_{LW}(t,s,r) + C_{HC}(t,s,r) \right] \le C_C^P(t)$,

Transportation of Chips for Pulpwood and Energy ($t = 0, \dots, T$)

(14) $T_{CM}(t,0) + T_{CE}(t,0) \le \sum_{r=1}^{R} \left[C_{LW}(t,0,r) + C_{HC}(t,0,r) \right]$,

(15) $T_{CM}(t,s) + T_{CE}(t,s) \le \sum_{r=1}^{R} \left[C_{LW}(t,s,r) + C_{HC}(t,s,r) \right] + I^{CF}(t-1, s-1)]$, for $s = 1, \dots, L-1$,

Capacity Limits on Chips Transportation ($t = 0, \ldots, T$)

(16) $\sum_{s=0}^{t\wedge L}\left[T_{CM}(t,s) + T_{CE}(t,s)\right] \le C_C^T(t)$,

Capacity Limits Total Transportation ($t = 0, \ldots, T$)

(17) $\sum_{s=0}^{t\wedge L}\left[T_{CM}(t,s) + T_{CE}(t,s)\right] + \sum_{s=0}^{t\wedge L}\sum_{r=1}^{R} T_L(t,s,r) \le C_{LC}^T(t)$,

End-of-Period Harvest Inventories ($t = 0, \ldots, T$)

(18) $I^{HL}(t,0,r) = H_L(t,0,r) - \frac{1}{\alpha}T_L(t,0,r)$, for $r = 1, \ldots, R$,

(19) $I^{HC}(t,0,r) = H_C(t,0,r) - C_{HC}(t,0,r)$, for $r = 1, \ldots, R$,

(20) $I^{LW}(t,0,r) = \mu\frac{1-\alpha}{\alpha}T_L(t,0,r) - C_{LW}(t,0,r)$, for $r = 1, \ldots, R$,

(21) $I_C^F(t,0) = \sum_{r=1}^{R}\left[C_{HC}(t,0,r) + C_{LW}(t,0,r)\right] - T_{CM}(t,0 - T_{CE}(t,0)$,

(22) $I^{HL}(t,s,r) = I^{HL}(t-1,s-1,r) + H_L(t,s,r) - \frac{1}{\alpha}T_L(t,s,r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$

(23) $I^{HC}(t,s,r) = I^{HC}(t-1,s-1,r) + H_C(t,s,r) - C_{HC}(t,s,r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$,

(24) $I_C^F(t,s) = I_C^F(t-1,s-1) + \sum_{r=1}^{R}\left[C_{HC}(t,s,r) + C_{LW}(t,s,r)\right] - T_{CM}(t,s - T_{CE}(t,s)$, for $s = 1, \ldots, L-1$,

Mill Production Processes and Limitations ($t = 0, \ldots, T$)

(25) $P_C^L(t,0,r) + \frac{1}{\beta}P_L(t,0,r) \le T_L(t,0,r)$, for $r = 1, \ldots, R$,

(26) $P_C^{LW}(t,0,r) \le \frac{1-\beta}{\beta}P_L(t,0,r)$, for $r = 1, \ldots, R$,

(27) $P_P^{MC}(t,0) + P_E^{MC}(t,0) \le T_{CM}(t,0) + \sum_{r=1}^{R}\left[P_C^{LW}(t,0,r) + P_C^L(t,0,r)\right]$,

(28) $P_C^L(t,s,r) + \frac{1}{\beta}P_L(t,s,r) \le T_L(t,s,r) + I^L(t-1, s-1, r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$,

(29) $P_C^{LW}(t,s,r) \le \frac{1-\beta}{\beta}P_L(t,s,r) + I^{PW}(t-1, s-1, r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$,

(30) $P_P^{MC}(t,s) + P_E^{MC}(t,s) \le T_{CM}(t,s) + I^{MC}(t-1, s-1) + \sum_{r=1}^{R}\left[P_C^{LW}(t,s,r) + P_C^L(t,s,r)\right]$, for $s = 1, \ldots, L-1$,

Mill Production Capacity Restrictions ($t = 0, \ldots, T$)

(31) $\sum_{r=1}^{R}\sum_{s=0}^{t\wedge L}P_L(t,s,r) \le C_L^M(t)$,

(32) $\sum_{r=1}^{R}\sum_{s=0}^{t\wedge L}\left[P_C^{LW}(t,s,r) + P_C^L(t,s,r)\right] \le C_C^M(t)$,

(33) $\sum_{s=0}^{t\wedge L}P_P^{MC}(t,s) \le C_P^M(t)$,

(34) $\sum_{s=0}^{t\wedge L}P_E^{MC}(t,s) \le C_E^M(t)$,

End-of-Period Inventories at Mills ($t = 0, \ldots, T$)

(35) $I^L(t,0,r) = T_L(t,0,r) - \frac{1}{\beta}P_L(t,0,r) - P_C^L(t,0,r)$ for $r = 1, \ldots, R$,

(36) $I^{PW}(t,0,r) = \frac{1-\beta}{\beta}P_L(t,0,r) - P_C^{LW}(t,0,r)$, for $r = 1, \ldots, R$,

(37) $I^{MC}(t,0) = T_{CM}(t,0) + \sum_{r=1}^{R}\left[P_C^{LW}(t,0) + P_C^L(t,0)\right] - P_P^{MC}(t,0) - P_E^{MC}(t,0)$,

(38) $I^L(t,s,r) = I^L(t-1,s-1,r) + T_L(t,s,r) - \frac{1}{\beta}P_L(t,s,r) - P_C^L(t,s,r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$

(39) $I^{PW}(t,s,r) = I^{PW}(t-1,s-1,r) + \frac{1-\beta}{\beta}P_L(t,s,r) - P_C^{LW}(t,s,r)$, for $s = 1, \ldots, L-1$, and $r = 1, \ldots, R$,

(40) $I^{MC}(t,s) = I^{MC}(t-1,s-1)\ T_{CM}(t,s) + \sum_{r=1}^{R}\left[P_C^{LW}(t,s) + P_C^L(t,s)\right] - P_P^{MC}(t,s) - P_E^{MC}(t,s)$, for $s = 1, \ldots, L-1$,

Chips Energy Conversion (o = Other Locations; ($t = 0, \ldots, T$)

(41) $P_E^{oC}(t,0) \le T_{CE}(t,0)$,

(42) $I_E^{oC}(t,0) = T_{CE}(t,0) - P_E^{oC}(t,0)$,

(43) $P_E^{oC}(t,s) \leq I_E^{oC}(t-1,s-1) + T_{CE}(t,s)$ for $s = 1, \ldots, L-1$,

(44) $I_E^{oC}(t,s) = I_E^{oC}(t-1,s-1) + T_{CE}(t,s) - P_E^{oC}(t,0)$ for $s = 1, \ldots, L-1$,

(45) $\sum_{s=0}^{t \wedge L} P_E^{oC}(t,s) \leq C_E^{o}(t)$.

Example

To illustrate the system model, consider the following simplified example. An SPB outbreak in east Texas generates 300 tons/day of fresh kills during March, April, and May; 200 tons/day during June, July, and August; 100 tons/day during September, October, and November; and 0 tons/day during December, January, and February. Thus, in the model, we can use a 3-month time index: $t = 0$ for March, April, and May; $t = 1$ for September, October, and November; and so on. It is decided to set up a harvesting operation to recover the killed biomass. Trees less than 10 inches in DBH are chipped for pulpwood and/or energy generation, and those trees 10 inches or more in DBH are harvested as logs for lumber (or possibly later chipped for pulpwood and/or energy use). In the infestation area, the forest averages 45% biomass with less than 10 inches DBH. The model is started from the first of the outbreak, so all initial inventories are zero.

A typical harvesting operation consists of one feller buncher (for cutting trees), one grapple skidder (for gathering trees together and hauling them to a landing; capacity 150 tons/day), and one whole-tree chipper (capacity 150 tons/day). The proportion of the biomass of a tree that is logged is about 65%, leaving the remaining 35% biomass as waste. This biomass waste is frequently left in the field, but with this dual chipping and logging harvesting operation, this waste biomass can also be chipped. At the mill, saw timber production from logs results in an additional 25% waste, which can be chipped for pulpwood use at the mill. The harvest operation has four trucks for hauling the products to the mill and/or the energy sites. Two trucks are dedicated to hauling logs, and two are dedicated to hauling chip containers. Each truck can haul approximately 75 tons/day, assuming about a 50-mile one-way trip, so the capacities of the hauling subsystems are not limiting.

The economic drivers for this harvesting operation are that saw logs are valued at \$66.70/ton and chips at \$30.50/ton at the mill. These are costs based on the harvester operator's point of view. Stumpage costs (payments to the land owners for the trees) are \$40/ton for saw timber and \$6.50/ton for pulpwood. The lumber and pulpwood values represent about a 15% profit over typical costs. The energy use option is not available for this example, because the processing capacities of the mill are assumed to be sufficient to handle both log and pulpwood harvests from this site as well as the additional waste-chipping requirements. Saw timber harvesting costs \$12/ton, and pulpwood harvesting costs \$12/ton plus \$2/ton for chipping. Transportation costs are \$6/ton for both logs and chips. Also needed for the model are the decay estimates for the biomass as a function of age since being killed. For sawtimber, in east Texas, we estimate that this is usable for only one time period, while pulpwood decays at period rates of 0%, 50%, 75%, and 100% for the four periods of the model. That is, pulpwood has totally decayed in value after 1 year. Cost data used in this example were taken from two general sources: a Texas Forest Service (n.d.) case study and Timber Mart-South's (2005) fourth quarter press release for 2005.

The model resulted in a linear programming problem with 480 variables and 220 constraints in the software ILOG CPLEX. The solution time was almost instantaneous. A model generator was written in Microsoft's Visual Basic .NET and interfaced with CPLEX to submit the problem and retrieve the solution results. The optimal solution results are as follows.

Period 1 (Harvest Limit 150 Tons/Day)

The harvest is 150 tons/day of sawtimber (trees 10 inches or more in DBH) and 0 tons of pulpwood. The yield is 97.5 tons/day of logs and 52.5 tons/day of chips in the field. Ultimate production is 73.125 tons/day of timber and 76.875 tons/day of pulpwood.

Period 2 (Harvest Limit 150 Tons/Day)

The harvest is 110 tons/day of sawtimber (trees 10 inches or more in DBH) and 40 tons of pulpwood. The yield is 71.5 tons/day of logs and 78.5 tons/day of chips in the field. Ultimate production is 53.625 tons/day of timber and 96.375 tons/day of pulpwood.

Period 3 (Harvest Limit 150 Tons/Day)

The harvest is 55 tons/day of sawtimber (trees 10 inches or more in DBH) and 45 tons of pulpwood. The yield is 35.75 tons/day of logs and 64.25 tons/day of chips in the field. Ultimate production is 26.8125 tons/day of timber and 72.4375 tons/day of pulpwood.

Period 4 (Harvest Limit 150 Tons/Day)

There is no harvest because there is no new damage, and old, damaged biomass is not profitable.

These results are consistent with the cost and profit data used. Only first-period biomass is profitable to harvest (note that a period here is 3 months), and with the decline in the infestation over time, the harvest capacity is not reached during the third and fourth periods.

Conclusions

The issue of the utilization of disturbance-generated plant biomass has been ignored. Each SPB outbreak and hurricane event produces a large quantity of plant biomass that is wasted because various utilization pathways have not been defined. The Energy Policy Act of 2005, which President Bush signed into law on August 8, established a new national minimum requirement for the use of biofuels, particularly ethanol. The act requires the federal government, by 2013, to buy at least 7.5% of its electricity from renewable energy sources. The economic and social values of disturbance-generated plant biomass in the southern United States have not been evaluated, but they are thought to be substantial. Titles 1 ("Hazardous Fuel Reduction on Federal Land"), 2 ("Biomass"), and 4 ("Insect Infestations and Related Diseases") of the Healthy Forests Restoration Act have substantial components dealing with the reduction of hazardous fuel loads, returning federal forestlands to conditions that resemble more natural states, and the utilization of plant biomass. Biomass reduction is a fundamental component of the restoration process, and it will generate substantial and predictable quantities of raw material. The environmental issues associated with the utilization of disturbance-generated plant biomass have not been evaluated. Herein, we present an optimization-based system model that provides a means to investigate the various utilization pathways in an objective manner.

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