International Agricultural Engineering Journal 2009, 18(1-2):51-58

ALMANAC: A POTENTIAL TOOL FOR SIMULATING AGROFORESTRY YIELDS AND IMPROVING SWAT SIMULATIONS OF AGROFORESTRY WATERSHEDS

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ABSTRACT

The Soil and Water Assessment Tool (SWAT), a robust watershed scale hydrological model, would benefit from the improvement of its plant model subroutine. To be applicable to agroforestry, the process-oriented plant model needs to be capable of simulating interspecies light competition, as well the water balance and nutrient balance of interacting crops, grasses, and woody species. It must also be able to consider short and long term effects of various management and climate scenarios. Here we describe the usefulness of the general plant competition model Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) in this capacity. Further, we discuss a version of the model ($ALMANAC_{BF}$) that realistically simulates complex successional changes in mixed coniferous and deciduous boreal forest ecosystems. For application to agroforestry in a tropical context ($ALAMANC_{TF}$), plant physiological parameters need to be developed for relevant species and algorithms derived to describe particularities of management systems. Simulation scenarios could then be conducted and compared to forest inventory data to determine the accuracy of $ALMANAC_{TF}$ in tropical systems. Current incorporation of ALMANAC into SWAT, including $ALMANAC_{BF}$ capabilities, will improve the accuracy of watershed scale simulation of plant competition and agroforestry systems, and provide a basis for developing improved tropical systems routines. Accurate simulations will enable agroforesters and policy makers to adopt the most economically and ecologically sound management strategies at the farm and watershed scale.

1. INTRODUCTION TO ALMANAC AND SWAT

The Soil and Water Assessment Tool (SWAT) is a process-based hydrological and water resources assessment model that was developed to determine the effects of various management scenarios on water resources at the watershed scale (Arnold et al., 1998; Arnold and Forher, 2005; Gassman et al., 2007). The plant growth model currently embedded in SWAT assumes a uniform, monotypic plant stand (Krysanova and Arnold, 2008). Agroforestry simulations by SWAT would be improved by the incorporation of a plant growth model capable of simulating competition and dynamic vegetation changes over time (Arnold and Forher, 2005). Agroforestry plant communities are complex systems composed of taller woody species competing with shorter grass or crop species for light, water, and nutrients. Realistic watershed scale simulations of hydrological processes in these systems require a comprehensive, realistic process-based model capable of simulating competition for light, water, and nutrients on species growth and development, and effective at partitioning biomass among and within trees, crops, and grasses. Herein we describe just such a robust model, the Agricultural Land Management Alternatives with Numerical Assessment Criteria Model (ALMANAC; Kiniry et al., 1992).

ALMANAC has been successfully applied to a large number of crop, grass, and tree species, as well as diverse managed and unmanaged communities. Part of the reason for the wide use of ALMANAC is the ease with which parameters may be derived from existing parameters for other, similar species, or developed with straightforward field work. With species-appropriate physiologically based parameters, ALMANAC's simulations of biomass production and seed yields have been validated at various locations across North America under a variety of climatic

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conditions (Kiniry et al., 1992; Kiniry and Bockholt, 1998; Yun et al., 2001). Further, parameters for range grasses and both native and improved pasture grasses were developed and validated at diverse sites across North America (Kiniry et al., 1996; Kiniry et al., 1999; Kiniry et al., 2002; Kiniry et al., 2007; McLaughlin et al., 2006).

In agroforestry systems the tree component often plays a dominant role in determining the light, nutrient, and water resources available to other species in the system (Rao et al., 1998). ALMANAC has demonstrated capacity to simulate woody species and forest re-growth. Parameters for the woody evergreen eastern red cedar (*Juniperus virginiana* L.) and leguminous mesquite (*Prosopis glandulosa* Torr. var. *glandulosa*) were developed more than ten years ago, demonstrating the utility of ALMANAC for simulating woody species (Kiniry, 1998). Recently, ALMANAC was altered and parameterized to more effectively simulate forestry applications in boreal forests (MacDonald et al., 2008), resulting in a new version of model, $\text{ALMANAC}_{\text{BF}}$, which can predict tree, grass, shrub, and forb interactions under a variety of conditions. This is a desirable development for land managers, who need to be able to quantitatively predict agroforestry tradeoffs between various cropping methods with various species of trees and crops across a wide variety of soils and climates (Huth et al., 2003).

The use of ALMANAC and $\text{ALAMANC}_{\text{BF}}$ to simulate tree growth in the North American context suggests that ALMANAC could be successfully modified to create a tropical forest version ($\text{ALMANAC}_{\text{TF}}$) capable of simulating tropical systems, such as the tropical agroforestry systems found in southeast Asia. Agroforestry cropping systems must manage both environmental and sylvicultural effects on crops, which make maximizing production by all species in the system impossible. The ability to model species specific effects on the spatial distribution of light, nutrients, and water will greatly assist in planning and executing tree-crop systems (Everson et al., 2009). With appropriate modifications, $\text{ALMANAC}_{\text{TF}}$ will be able to simultaneously simulate tree growth and canopy development in parallel with the growth of shrubs grasses and forbs in a tropical setting. A working version of SWAT that includes $\text{ALMANAC}_{\text{BF}}$'s light competition algorithms and tree growth algorithms is currently being further validated and modified appropriately. The hypothetical $\text{ALMANAC}_{\text{TF}}$ model could be developed directly in SWAT based on these algorithms. As a component in SWAT, the model could help better model impacts and yields in large area simulations of dynamic, tropical agroforestry systems. Herein we present the argument for the development of $\text{ALMANAC}_{\text{TF}}$.

2. $\text{ALMANAC}_{\text{BF}}$ FOR AGROFORESTRY SIMULATION

$\text{ALMANAC}_{\text{BF}}$ was designed to simulate boreal forest succession, including initial stages after timber harvest, when vegetation is dominated by annual and perennial forbs and grasses. On the Canadian Boreal Plain, forest disturbance triggers successional forest regeneration, where the community transitions from one dominated by annual forbs and perennial grasses, to shrubs, until the mature forest composed of mixed or pure stands of coniferous and deciduous species develops (Smith et al., 2003; Beckingham and Archibald, 1996). For $\text{ALMANAC}_{\text{BF}}$ to be applicable to forest management, it needed to, not only accurately simulate key species growth, but also account for the successional forest dynamics without spending excessive simulation time on the complexities of forest growth.

For SWAT to simulate agroforestry impacts on water quantity and quality, the forest growth module of SWAT requires major modifications. To accurately simulate the key processes of forest hydrology impacted by forest management practices, simulations of multi-species interactions are required (Arnold and Forher, 2005). Existing forest growth models tend to be complex and data intensive (Running and Coughlin, 1988; Kimmins et al., 1999; Van Noordwijk and Lusiana, 1999; Peng et al., 2002). While simpler models exist (Landsberg and Waring, 1997), they are limited to simulating even aged monocultures. Since the largest impact on water quantity and quality in forests occurs in the first ten years after disturbance (Burke et al., 2005; Prepas et al., 2006), the $\text{ALMANAC}_{\text{BF}}$ model was developed to be integrated into SWAT as a forest disturbance and re-growth module. With the multi-species algorithms already in ALMANAC, the development of $\text{ALMANAC}_{\text{BF}}$ algorithms emphasized the successional changes in vegetation in these initial stages after disturbance.

The $\text{ALMANAC}_{\text{BF}}$ algorithms developed to simulate initial stages of boreal forest recovery after disturbance may be particularly applicable to tropical agroforestry systems. Because tropical agroforestry systems are subjected to periodic disturbance regimes, $\text{ALMANAC}_{\text{BF}}$, which accounts for periodic disturbance, is a good platform for building a model capable of modeling such systems. Tropical agroforestry applications would need to be able to simulate the environmental impacts of both annual or perennial crops as well as the successional and later, understory forest vegetation dynamics. $ALMANAC_{BF}$ contains algorithms specifically designed to describe the development of forest canopies and as well as commercial tree characteristics. Further, the relatively simple light partitioning algorithms allow $ALMANAC_{BF}$ to simultaneously simulate the overstory canopy and perennial or annual plants growing under the canopy.

2.1 Effectively Simulating Commercial Tree Characteristics

The complete $ALMANAC_{BF}$ model is described in detail elsewhere (MacDonald et al. 2008). Briefly, like crop growth in SWAT, tree growth is simulated with light interception using Beer's law, and a species-specific value of radiation use efficiency (RUE) to calculate daily potential biomass accumulation. The model uses sigmoid curves ("s curves") based on growth degree day to describe annual growth (deciduous bud burst and conifer flush) (Phillips, 1950). Likewise, to simulate the gradual establishment of species on a site over time, sigmoid equations are used to describe long-term height and leaf area growth, using year as the dependant variable as opposed to heat units.

$ALMANAC_{BF}$ uses an empirical approach to describe forest growth based on stand structure. In natural forests, as is the case in agroforestry plantations, as forest stem density increases, individual tree size decreases (Plonski, 1974). The model uses species specific allometric equations to partition biomass into different woody and foliar biomass (MacDonald et al., 2005; MacDonald et al., 2008) by back calculating the average diameter at breast height for a tree species (DBH_i) from the stem number (Ter-Mikaelian and Korzukhin, 1997). Foliar biomass and branch biomass can then be calculated using an additional allometric equation based on simulated DBH_i.

Leaf area index is proportional to foliar biomass, which is a function of stem number. Consequently, stand productivity is proportional to stem density and the distribution of biomass among the different compartments within the tree (foliar, stem, branch and rooting systems). High density forest stands have smaller trees with a lower ratio of foliar biomass to stem biomass (and lower leaf area index). Net annual aboveground biomass production (NPP) for a specific tree species is calculated by subtracting annual foliar losses, based on the allometric calculation of foliar biomass from gross annual production (GPP) for that specific tree species. $ALMANAC_{BF}$ considers different stem densities as determined by site conditions, which then affects simulated productivity of the site.

As a consequence the commercial aspects of the forest stand can be determined (such as wood volume) and furthermore, annual nutrient uptake cycles are also simulated with the calculation and partitioning of plant biomass among the different parts of the plants (Figure 1). The simulation of biomass partitioning by different species to particular organs and tissue types changes over a plant's lifetime. It is essential to effectively simulate these changes in order to capture the changes in nutrient requirements and nutrient partitioning over time. This aspect of $ALMANAC_{BF}$ is particularly relevant to tropical agroforestry systems interested in managing multiple species for different yield goals (green manure, wood, fruit, bark, flowers, etc.). In the agroforestry context, relationships between tree planting density, tree growth and site productivity would have to be derived from experimental data.

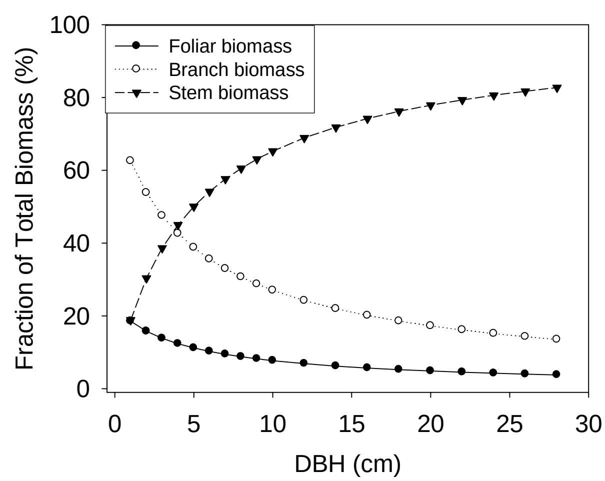

Fig. 1: Distribution of biomass among the branches, stem and leaves of a deciduous trembling aspen (*Populus tremuloides*) tree species as calculated by allometric equations in the $ALMANAC_{BF}$ model based on allometric equations from Ter-Mikaelian and Korzukhin (1997)

2.2 Multilevel Canopy Simulation Algorithms

ALMANAC's light partitioning algorithms distribute photosynthetic radiation (PAR) between different species based on species specific physiological parameters. The proportion of PAR intercepted by an individual species in the canopy is a function of its light extinction coefficient, its proportion of the total leaf area and its height (Kiniry et al., 1992). This approach, describes the filtering of PAR as it passes through the plant canopy. For species less than half the height of the tree species, the light interception is principally a function of the leaf area index of the dominant overstory tree species (Figure 2).

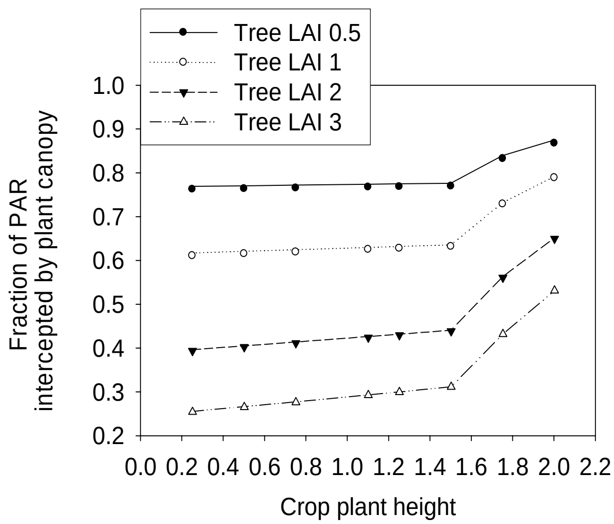

Fig. 2: Light interception of understory crop species under varying levels of leaf area index and consequently light competition by overstory trees. The leaf area is varied between 0.5 and 3 $m^2 m^{-2}$ and the competing trees are 3 m tall and have a Beer's extinction factor of 0.45

There is also a physical effect of canopy shading on plant growth. As the height and leaf area of the upper canopy increases, the area available to shorter species with adequate light to grow becomes limited, and therefore their potential LAI decreases (Lieffers and Stadt, 1994). As canopy height increases, annual potential LAI for vegetation under the canopy cover is limited (Figure 3). Different plants have different reactions to shading and the introduction of a light sensitivity factor (LTSNS) defines how a species reacts to shading. Species with high shade tolerance tend to invest greater proportions of available resources to maintain leaf area under light stress. This factor will define the maximum potential leaf area that an understory species can reach under a given tree canopy.

In the case of boreal forest canopies, there is a gradual shift from short perennial species to trees over the first 10 years, as the over-story canopy forms. Once that occurs there is a reduction in the growth of the lower species due to light and space limitations. In the case of tropical agroforestry, a similar evolution will occur as tree species begin to develop more ample canopies over the crop species. Once again experimentation will be required to develop parameters for the tree canopies and for different crop species reactions to shading at different plant heights and canopy development.

However at the same time there is a reciprocal effect on the growth of trees due to competition during tree establishment (Figure 4). Using relatively simple algorithms the $ALMANAC_{BF}$ model is produces a realistic simulation of the physical competition between tree species and annual or perennial species. While the model will require a certain amount of calibration and validation to be applied to tropical agroforestry problems, the fundamental algorithms required to simulate growth in complex, multi-canopy boreal agroforestry environments are sound and will provide an excellent starting point for simulating tropical agroforesty systems.

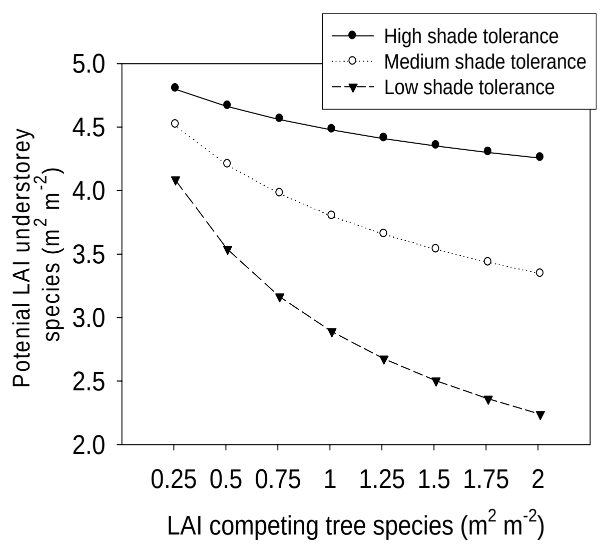

Fig. 3: Limitations to potential leaf area index for species with differing degrees of shade tolerance. The competing tree species are fixed at 10 m height and have a Beer's extinction factor of 0.45

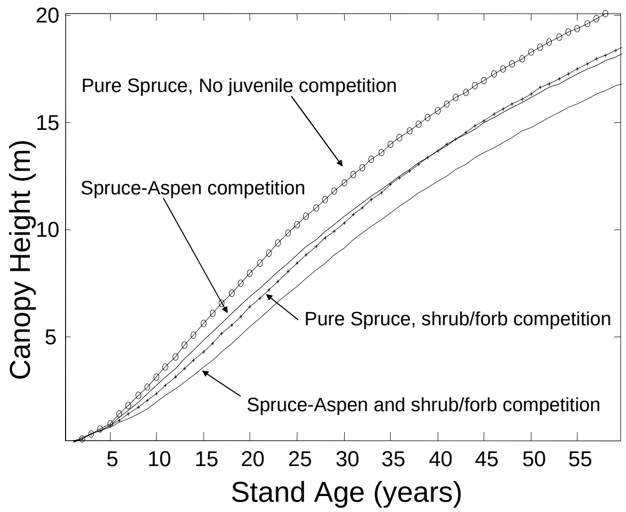

Fig. 4: Monoculture and polyculture tree growth with differing competition regimes, demonstrating tree-shrub interaction and recovery after disturbance

3. WATER AND NUTRIENT COMPETITION

ALMANAC was originally designed to simulate weeds competing with crops (Kiniry et al., 1992). ALMANAC incorporates the light competition equations of Spitters and Aerts (1983) and simulates competition among species for water and nutrients. Water balance and nutrient balance are simulated for each plant species in the system, with reductions in leaf area growth and biomass production if either water or nutrients are insufficient to meet demand. Water demand (potential evapotranspiration) for each species is based on atmospheric demand and plant leaf area cover. Demand for nutrients is based on optimum nutrient concentrations (which are species specific and vary according to development stage), rooting depth, and available nutrients in the current rooting depth of the soil.

4. THE FUTURE OF ALMANAC$_{TF}$

Agroforestry systems are incredibly complex and varied, such as those described by Reyes et al. (2008). System approaches are determined by climate, topography, economic and ecological objectives, as well as species composition. Managers determine their interacting species as well as the manner in which species interact by spatial and temporal methods, including hedgerow intercropping with annual or perennial crops, scattered trees in croplands, boundary trees, and rotational or sequential cropping systems (Rao et al., 1998). Tree-crop intercropping is driven by various goods and services objectives, making optimal management strategies harvest objective dependent (Everson et al., 2009). At present, accurate quantification of the impacts that various woody species within different management scenarios have on soil water content, nutrient cycling, and crop production across the variety of agroforestry systems is lacking (Teixeira et al., 2003).

Light is not the only limiting factor in tropical agroforestry systems. Root interactions and competition for water and nutrients are also means by which trees and understory crops interact. Possible beneficial effects of woody species on microclimate and nutrient availability for understory species during specific periods of rotational sequences may not become apparent for many years post-establishment (Rao et al., 1998). On the other hand, some nitrogen fixing legumes (*Acacia* spp.) have been shown to fix substantial amounts of nitrogen in the initial years following establishment (Khanna, 1998). Interactions between species are site-specific. For example, spatial complementarity noted between trees and crops in regards to soil water use is only apparent when trees are deep rooted and able to access a deep water source or when water is a non-limiting resources (Everson et al., 2009). Otherwise, hydraulic redistribution by deep rooted tree species may be deleterious to water availability in shallower rooted species (Burgess et al., 1998). In semi-arid tropical climates soil water depletion by hedgerow species can lead to lower yields by intercropped species (Govindarajan et al., 1996). Feldhake (2009) found that though trees modified microclimate for understory forage, the trade-off between the water savings benefit of decreased forage evapotranspiration and cost of PAR interception stress caused by the overstory were determined by plant spacing.

To apply ALMANAC to tropical systems, the necessary parameters need to be developed for pertinent species and management scenarios. These include Beer's law coefficients, leaf area development parameters, nutrient use efficiency, radiation use efficiency, and estimates of shade sensitivity for all crop species. These physiological parameters will require validation across various climates and soils, as species interactions and management approaches in tropical agroforestry systems vary considerably due to soil fertility (Rao et al., 1998). The products and services desired from these multifunctional systems vary radically. The harvestable end goal may be a product like bark, latex, flowers, fruits, seeds, or wood, or it may be a service like forage, soil stability, biological nitrogen fixation, biodiversity maintenance, carbon sequestration, or rural socio-economic viability (Muetzelfeldt, 1995; Bengtsson et al., 2000; Everson et al., 2009). Maximizing yields of one agroforestry product or service can be deleterious to another aspect; research must be focused on the ecological and physiological trade-offs that arise in tropical agroforesty systems (Jordan et al., 2007).

With the development of physiological parameters for specific species under optimal conditions, the site specific interactions between species can be studied and thus modeled more effectively. Many of these interactions are already under study, as it is the optimizing of interactions between woody species and non-woody species that epitomizes agroforestry success (Rao et al., 1998). To effectively develop ALMANAC into $ALMANAC_{TF,}$ further work on nutrient and water competition algorithms are needed. These changes will require development and validation of below ground biomass estimates and rates of production to better model water and nutrient interactions between species.

Canopy architecture is a critical element in light, water, and nutrient competition. Trees express different architecture under different ecological conditions, including under various agroforestry applications such as hedgerow cropping as compared to scattered trees in croplands (Rao et al., 1998). Manceur et al. (2009) found that when grown under tree species with high crown volume, understory soybean crops decreased biomass allocation to structural tissues and petioles, leading to lower overall yields than under low-volume tree canopies. Further study of the effects of cropping on the geometry of tree canopies, resultant stem flow, and light interception patterns under different management systems is needed. $ALMANAC_{TF}$ needs to be parameterized for these dynamic production systems in order to appropriately account for the allocation of biophysical resources in such systems. Furthermore, the physical impact of the presence and distribution of trees on microclimate will be quantified and specific algorithms will be developed into ALMANAC to account for these effects. Due to the compartmentalized structure of deterministic models such as ALMANAC and SWAT, these changes would be relatively easily achieved.

Finally, it is important to note that the interactions between tropical agroforestry species for light, nutrients, and water are complex and change over time as some species mature or are harvested out of the system. The use of livestock in some tropical systems increases the system complexity, including redistribution of nutrients and effects of selective grazing. The importance of collecting relevant, sequential data on a variety of tropical agroforestry management systems across a variety of climates and soils to quantitatively account for variability in theses systems cannot be over-emphasized. In addition to allowing us to better model these systems, collecting parameters relevant to $ALMANAC_{TF}$ will further our understanding of forest dynamics and ecosystem processes as affected by current management scenarios, which will lead to better agroforestry management decisions (Bengtsson, et al., 2000).

5. CONCLUSION

Agroforestry systems combine woody perennial management with cropping systems or livestock operations, either as a simultaneous, but heterogeneous spatial mixture or in temporal sequence (Leakey, 1996). ALMANAC is capable of considering complex agroforestry systems managed in either way. $ALMANAC_{BF}$ realistically simulated successional stages in forest growth as well as watershed scale variations in stand characteristics in mixed and pure forest canopies in Canadian Boreal forests. In tropical forest systems such as those found in Southeast Asia, simulation scenarios could be conducted and compared to forest inventory data to determine the accuracy of the current model parameters. With some modification to better fit tropical systems, the proposed $ALMANAC_{TF}$ shows potential as a tropical forestry modeling system, capable of assisting land managers in making decisions that will improve the sustainability of land use, improve the productivity of the managed system, and provide better economic stability to the community or individuals managing the system.

SWAT's current plant growth model was developed for crops grown in monoculture (Krysanova and Arnold, 2008). Quantifying the appropriate model inputs for tropical agroforestry systems is a daunting, but necessary task. The ALMANAC model has shown tremendous flexibility and promise in new systems. Ongoing incorporation of the ALMANAC plant growth routines into SWAT will increase the robustness of the SWAT model by allowing simulation of overseeded cropping systems, Boreal forest systems, and other scenarios with mixed vegetation. Further refinement of parameters in tropical agroforestry systems will allow the development of an improved SWAT model that can be used for watershed-scale tropical agroforestry assessments. Such improvements are imperative if modelers hope to simulate the diversity of benefits and services provided by tropical agroforestry species and systems at both local and watershed scales, as well as at various temporal scales (Jose, 2009).

Continued development and integration of SWAT and ALMANAC will be driven by user-demand. Working in combination, these models may prove a valuable tool to tropical agroforestry managers interested predicting the effects of multifunctional agroforestry management techniques at field-scale and watershed scale under various climate scenarios.

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