UNDERSTANDING THE RELATIVE IMPORTANCE OF FOREST CANOPY DEVELOPMENT AND LEAF LITTER ACCUMULATION ON SOIL EVAPORATION

by

TYLER ELLIS MCINTOSH

(Under the Direction of Doug Aubrey and Rhett Jackson)

ABSTRACT

Forest productivity and water use efficiency are tightly linked to forest evapotranspiration. Most evapotranspiration studies focus on bulk trends over entire rotations and downplay the dynamics of soil evaporation in early stand development prior to canopy closure or in response to management activities (i.e., raking, thinning, etc.). Our objectives were to determine the relative importance of leaf litter and canopy leaf area (i.e., shading) on forest soil evaporation, formulate correction coefficients (K_c) based on the FAO-PM model to predict soil evaporation given variable leaf litter and canopy shade levels, and use a modelled leaf-area-index (LAI) to explain responses of soil evaporation to variable forest control conditions. Results suggest that litter limits soil evaporation more than canopy shade, soil evaporation is explained well by modelled LAI, and K_c coefficients can be used for various forest management scenarios. These results may be used to inform better litter and canopy related forest management decisions in the future.

INDEX WORDS: Soil evaporation, forest hydrology, reference evapotranspiration

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Chapter 1: INTRODUCTION AND LITERATURE REVIEW

Short rotation woody crops (SRWCs), principally grown for woody biomass in accelerated rotations that are less than half the length of traditional long rotation silviculture, have the potential to supply a sustainable source of biomass and fiber for pulp (Domec et al., 2017; Tuskan, 1998). SRWCs spend relatively more time in transitional phases or in early-stage development due to the shorter time between harvests, and thus support different evapotranspiration time series and water budgets. Recent research has revealed that bare soil evaporation can be a substantial portion of the water budget of young forest plantations (Younger et al., 2023). However, the dynamic controls of changing litter density and canopy shade on soil evaporation E_s in young plantations have received little research attention.

A common practice in assessing the impact of forests on the hydrology of a given area of land is to generate a water budget with inputs and outputs. Precipitation is the input to the forest water budget. The outputs of water in a forested stand are interception, soil evaporation, and transpiration (the three components of evapotranspiration or ET) and losses to streamflow generation processes, including percolation to groundwater, interflow, and surface runoff. Soil water storage is variable and can account for losses or additions in water balance equations (Figure 1).

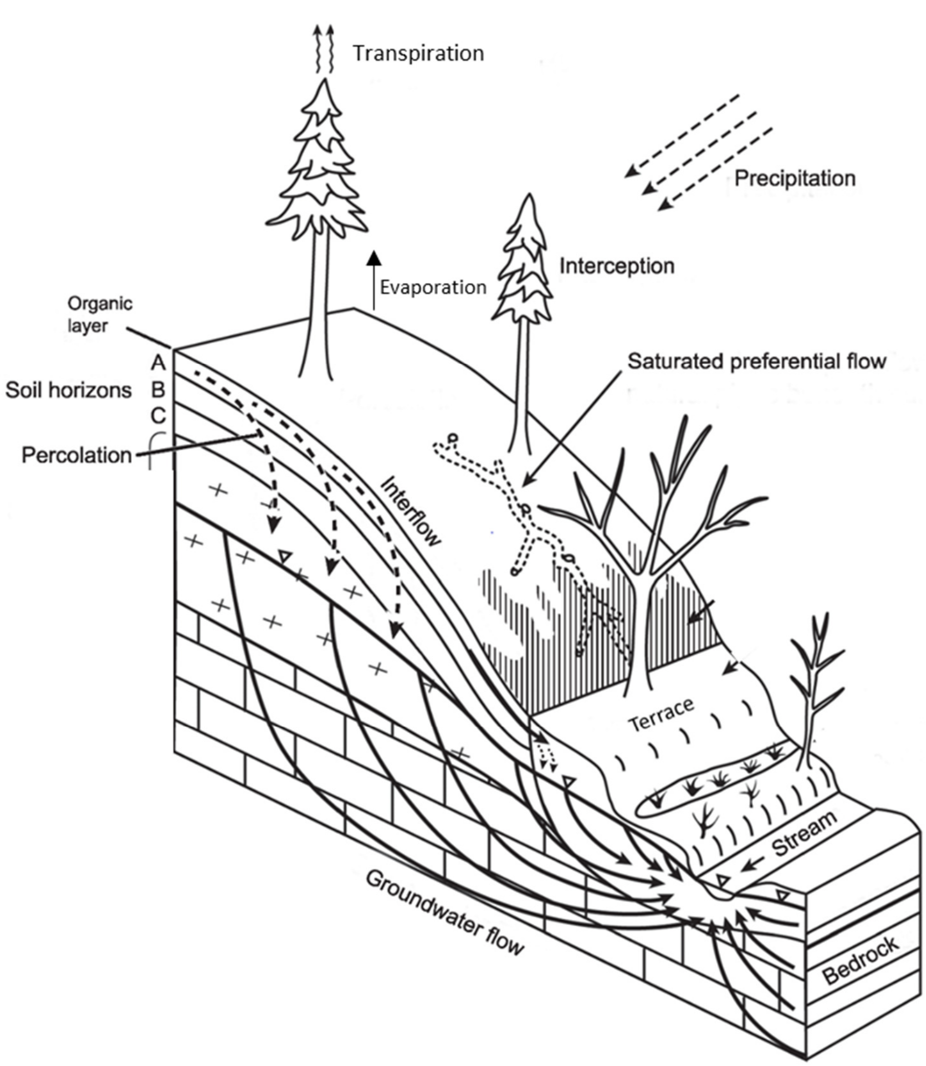

Figure 1.1. A conceptual model of the hydrologic processes involved in water budget construction. This is adapted from Klaus, J. and C.R. Jackson. 2018. (Klaus and Jackson, 2018)

ET is defined as the cumulative water loss from a vegetated area by the processes of transpiration (E_t) and evaporation (E_s). E_t is the water loss through stomatal pores of plants and is facilitated by photosynthesis. E_s is water that evaporates from soil and from surfaces that intercept precipitation. Methods of estimating ET have been developed to include fluxes of lateral flow, infiltration and soil moisture storage in water balance and

ET calculations (Mandana Rahgozar, 2012; Schicht and Walton, 1961). The dynamics of forests (i.e. the accumulation of leaf litter and increase in canopy shading) have the potential to influence the components of ET.

As leaves senesce and fall, they accumulate on the ground and influence soil hydrology in terms of water and energy available for ET. In early stand development, leaf litter inputs to soil from both evergreen and deciduous crops tend to outweigh decomposition outputs until the two processes reach an equilibrium (Olson, 1963). The point in time where equilibrium is achieved depends on species litter production, meteorological conditions, chemical properties of litter, and the rate of consumer metabolism (Olson, 1963). As an example, *Pinus taeda* plantations in the southeastern US have a relatively high rate of litter production compared to the maximum capacity for forest floor litterfall at equilibrium, so these crops tend to reach equilibrium comparatively quickly (~10 years) (Metz, 1952; Olson, 1963). Before and after equilibrium is reached, accumulated litter creates a barrier to water inputs on top of the soil. It shields the soil from solar radiation and fluctuations in temperature (J. Ogèe, 2002) and stored water (Sayer, 2006). Interception and retention of precipitation by litterfall can account for anywhere from 0.2% (Neto et al., 2012) to 40% (Walsh and Voigt, 1977) of annual precipitation (Acharya et al., 2017). The wide range of values for this are due to differences in precipitation amount, litter type and litter mass. It has been shown that the litter of a broadleaf species will retain more water than the litter of a needle-bearing species, and across the litter of different species, more mass per unit area corresponds to a greater potential for water retention (Walsh and Voigt, 1977). Leaf litter within forested stands has also been shown to alter the physical characteristics of the soil below the canopy (Sayer, 2006). Litter presence also influences soil bulk density. The topsoil layer of raked stands can exhibit nearly double bulk the density of their unraked counterpart (Mitscherlich, 1955).

Canopy shading has been shown to affect the evaporative properties of the soil below. A forest canopy increases relative humidity of the understory and reduces wind speed, temperature, and the amount of solar radiation at the soil surface (C.S.B. Grimmond, 2000). One method of quantifying the ability for a canopy to block irradiance is to measure the leaf area index, or LAI, under the canopy. LAI is defined as the ratio of one-sided leaf area to the unit ground surface area. Recent work suggests that E_s in bare plots and in early stand development can be a significant source of water loss and that the stands maximize E_t rates upon canopy closure and when a significant amount of LAI and leaf litter has been established (P.V. Caldwell, 2018; Vining, 2015; Younger et al., 2019). Most work that includes constructing water budgets focuses on bulk ET trends and does not focus on specific time periods within rotations. To our knowledge, studies that attempt to isolate and quantify the effect of leaf litter and canopy shade on E_s in forests are rare and none have compared observed E_s in response to forest controls to predicted values from popular predictive models.

To understand how ET is predicted, an understanding of empirical ET measurement is required. ET is typically measured in one of two ways: water budget methods and water vapor transfer methods (Shuttleworth, 2008). Water budget methods seek to deduce ET by measuring all other components in the water budget. A comprehensive water budget is suggested (R.G. Allen, 1998):

$$ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \quad (1)$$

Where *ET* is evapotranspiration (mm day^{-1}), *I* is irrigation (mm day^{-1}), *P* is precipitation (mm day^{-1}), *RO* is surface runoff (mm day^{-1}), *DP* is deep percolation (mm 8day^{-1}), *CR* is capillary rise (mm day^{-1}), *ΔSF* is the difference between subsurface flow into and out of the system (dmm dday^{-1}), and *ΔSW* is the change in the soil moisture content over the change in time (mm day^{-1}).

ΔSF, CR, RO and DP are difficult to measure in open systems. Lysimetry is used to measure ET with control of *ΔSF* and *DP*. This, along with the assumption that *CR* and *RO* are negligible simplifies equation 1:

$$ET=I+P-DP\pm\Delta SW \quad (2)$$

The water vapor transfer methods of measuring ET rely on the measurement of ET in terms of latent energy rather than a deduction from a water budget. One method of measuring latent energy transfer is by the eddy covariance method, which utilizes ultrasonic anemometers and infrared gas analyzers to estimate latent energy transfer (Burba, 2013). The above empirical methods have been used to create predictive models for E_s and overall ET.

The Penman equation estimates potential evaporation from bare soil and open water (Penman, 1948). This equation combines energy balance closure and mass transfer methods to derive an equation that is dependent on a few micrometeorological parameters (Shuttleworth, 2007): solar radiation, wind speed, air pressure, relative humidity, and air temperature.

$$E_0 = \frac{mR_n+\gamma * 6.43(1+0.536 * U_2)\delta e}{L(m+\gamma)} \quad (3)$$

Where E_0 is evaporation (mm/day), m is the slope of the saturation vapor pressure curve (kPa/K), γ is the psychrometric constant ($=0.0016286*P_{kPa}*L^{-1}$) (kPa/K), U_2 is the horizontal wind speed (m/s), δe is the vapor pressure deficit (kPa).

One major limitation of the Penman equation is that it does not account for variable surface or aerodynamic conditions such as soil density or vegetation cover. To combat this, the Penman-Monteith model, which includes bulk surface and aerodynamic resistance parameters, was created (Monteith, 1965):

$$ET = \frac{m(R_n - G) + \rho_a C_p \frac{\delta e}{r_a}}{L(m + \gamma\left(1 + \frac{r_s}{r_a}\right))} \quad (4)$$

Where G is soil heat flux ($MJ*m^{-2}*day^{-1}$), r_s is the bulk surface resistance to evaporation (s/m), and r_a is the aerodynamic resistance to evaporation ($s\ m^{-1}$)

Aerodynamic resistance depends heavily on vegetation architecture and height and can be difficult to determine if the vegetation does not completely cover the area of interest. It is defined by Monteith as:

$$r_a = \frac{\left(\frac{\ln(z-d)}{z_0}\right)^2}{k^2 u_z} \quad (5)$$

Where z is the height of the wind speed measurement (m), d is the zero-plane displacement height (m), z_0 is the roughness parameter (m) that dictates loss of aerodynamic movement, k is von Karman's constant (0.41), and u_z is the wind speed at height z.

Bulk surface resistance (r_s) is defined as the resistance to water vapor flow through transpiring plant surfaces and through soil evaporation. This variable is dependent on the availability of water to the area of interest and the development stage of the plants within the area. Allen et al (1998) suggests that an acceptable approximation of r_s in dense, full canopy cover conditions is:

$$r_s = \frac{r_i}{LAI} \quad (6)$$

Where r_i is the stomatal resistance (s m^{-1}) of an individual leaf and *LAI* is the sunlit leaf area index (m^2 leaf area * m^{-2}soil surface area) of the area of interest, r_i is dependent on species, climatic variables, and the diurnal cycle. *LAI* will increase as the canopy closes but it may be subject to seasonal fluctuations if, for example, the canopy is deciduous and persists for more than one year before harvest.

Determination of accurate r_s and r_a is difficult and not always possible. To combat this, the use of a standardized model with a short grass reference crop is suggested (R.G. Allen, 1998):

$$ET_0 = \frac{0.408m(R_n - G) + \gamma\frac{900}{T+273}u_z\delta e}{m + \gamma(1 + 0.34u_z)} \quad (7)$$

Equation 5 is the same as equation 2 but the parameters r_a and r_s have been solved for a short grass reference crop with a height of 0.12 cm, an albedo of 0.23, and a surface resistance of 70 s m^{-2}. The output for this equation can then be multiplied by one or more correction coefficients to determine a specific crop evapotranspiration rate (ET_c):

$$ET_c = K_c ET_0 \quad (8)$$

or

$$ET_c = (K_{cb} + K_e)ET_0 \quad (9)$$

Where K_c is the combined coefficient of the following: K_{cb} is the basal crop coefficient, and K_e is the soil evaporation coefficient.

Equation 8 is the single crop coefficient method and equation 9 is the dual crop coefficient method for calculating ET_c. Equations 8 and 9 have become the standard for the prediction of evapotranspiration in agriculture (Lakshman Nandagiri, 2005) and forestry (Stewart, 1988).

Soil evaporation generally occurs in two phases (Ritchie and Burnett, 1971). The first phase is defined as the energy limited phase in which there is sufficient water on or near the evaporating surface that the parameter that influences soil evaporation the most is the amount of energy available at the soil surface. This is referred to as potential evaporation (E_0) and is defined mathematically by equation 3. The second phase is defined as the water-limited phase in which there is insufficient water available at the soil surface for energy availability to be the main source of evaporative loss. In forests, applications of the P-M model to systems without a full cover canopy tend to underestimate ET, meaning that the model is not well suited to early forest stand development conditions. This is due to the assumption that ET that is predicted by the P-M model is under ideal energy-limited conditions (Farahani et al., 2007). Efforts have been made to assess the impact of water limited evaporation on the determination of K_c. Multiple coefficients were empirically derived for soil under a dry pasture and soil under a dry Chaco Forest with and without litter using micro-lysimeters (Magliano et al., 2017). These coefficients were later used to calculate the number of days necessary for the soil to reach a “water limited” state in each of the treatment conditions. We are unaware of other forest studies that create K_c coefficients for varying leaf litter and canopy shading conditions.

In this study, our objectives were to determine E_s under different levels of canopy shade and leaf litter accumulation to explore their individual and combined effects on E_s. Because leaf litter accumulation and canopy shading are not directly comparable, we sought to develop a model from our results and existing literature that relates each variable to LAI to further evaluate their relative effects on E_s. Finally, we sought to apply E_s coefficients derived from litter and canopy effects on E_s to management scenarios to predict actual and relative changes in Es that may occur from common forest management activities. We predicted that both litter accumulation and shade would exhibit negative relationships with E_s, litter accumulation would exert the stronger control, and the effects of the two predictors would be dependent. We expected that our LAI model would represent E_s dynamics during early stand development in that E_s would be high with no shade and litter and would decrease to an equilibrium as modelled leaf area increased.

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CHAPTER 2: UNDERSTANDING THE RELATIVE IMPORTANCE OF FOREST CANOPY SHADE AND LITTER ACCUMULATION ON SOIL EVAPORATION

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Abstract

Forest productivity and water use efficiency are tightly linked to forest evapotranspiration. Most evapotranspiration studies focus on bulk trends over entire rotations and downplay the dynamics of soil evaporation in early stand development prior to canopy closure. Our objectives were to determine the relative importance of leaf litter and canopy leaf area (i.e., shading) on forest soil evaporation, formulate correction coefficients based on an existing widely used model to predict soil evaporation given variable leaf litter and canopy shade levels, and use a modelled leaf-area-index (LAI) to explain responses of soil evaporation to variable forest control conditions. Results suggest that litter limited soil evaporation more than canopy shade, and soil evaporation is explained well by trends in modelled LAI, K_c coefficients can be used for various forest management scenarios. These results may be used to inform better litter and canopy related forest management decisions in the future.

2.1 Introduction

Evapotranspiration (ET) is a complex hydrologic process and understanding how it and its components change through forest stand development and in response to forest management practices can potentially improve our ability to manipulate forests for desired water use objectives. Forest ET is comprised of four parts: canopy interception, transpiration (E_t) from vegetation, and evaporation (E_s) from soil, (Allen et al., 1998). During early forest stand development, E_t is relatively low and increases with increasing leaf area index (LAI), whereas E_s is relatively high and decreases with increasing LAI and accumulation of litter on the forest floor (Younger et al., 2023). Total ET, and E_t itself, of forests has been well-studied, but forest E_s has been neglected as an important part of the water budget of forests and forest plantations. As a result, we lack a complete understanding of how ET and its components change through stand development and respond to forest management practices.

E_t and E_s are influenced by forest stand structure; however, we lack a mechanistic understanding of the primary forest structural controls on E_s. During early stand development, E_s in bare soil is large (P.V. Caldwell, 2018) and may vary depending on changing plant shading (Raz-Yaseef et al., 2010) and litter characteristics1 (Cui et al., 2022; J. Ogèe, 2002; Sayer, 2006) characteristics. As leaves expand and a canopy is established, it intercepts and reflects incoming radiation, reduces wind speed under the canopy (Oliver, 1971), and increases the amount of aerodynamic resistance of water vapor transfer to the atmosphere (Liu et al., 2006), thus reducing E_s. Crop residues or litter alter the soil's boundary layer with the atmosphere and create a second boundary layer (Park et al., 1998). Much like canopy, litter reduces the amount of incoming energy to the soil surface and simultaneously increases the aerodynamic resistance of water vapor transfer to the atmosphere (Sayer, 2006).

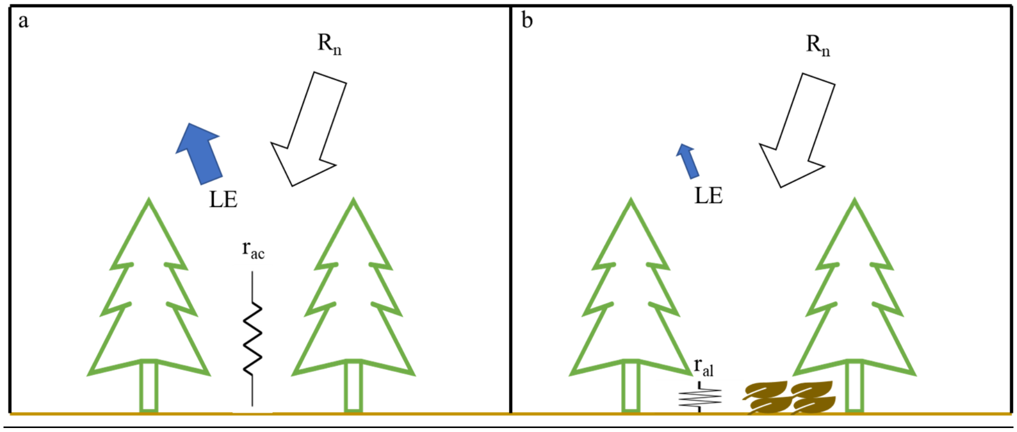

Figure 2.1. A conceptual model showing a) the resistance to radiation penetration and aerodynamic resistance to water vapor transfer (r_{ac}) in raked conditions with resulting relatively large latent energy transfer (LE), and b) the resistance to radiation penetration and aerodynamic resistance to water vapor transfer (r_{al}) in non-raked conditions with resulting relatively small latent energy transfer.

However, because the litter layer typically has a higher density of leaves on the evaporating surface, the energy interception, and the aerodynamic resistance to vapor transfer may be larger than those imposed by the canopy (**Figure 2.1**). Additionally, interception and retention of precipitation by litterfall can account for anywhere from 0.2% (Neto et al., 2012) to 40% (Walsh and Voigt, 1977) of annual precipitation (Acharya et al., 2017). The importance of using crop residues to limit E_s is recognized in agriculture, with a decrease in plant available water following removal of residues in maize (Berry and Mallett, 1988), and a reduction of E_s by 25% following an application of 8 t ha^{-1} of rice straw mulch in wheat (Eberbach et al., 2011). The relationships between litter characteristics and E_s in forests are less studied, despite the potential for litter to increase soil moisture content (Magliano et al., 2017) and transpiration (Lugo et al., 1978) in forests. We believe that a better understanding of the mechanistic controls of forests on E_s and overall ET will lead to a better understanding of forest management strategies in practice and in modelling.

Forest ET can be modeled from information about its structural characteristics and micrometeorological measurements. A preferable method of predicting a reference ET for a given area is the FAO-Penman-Monteith equation:

$$\mathrm{ET_0} = \frac{0.408\mathrm{m}(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T}+273} \mathrm{u_z} \delta \mathrm{e}}{\mathrm{m} + \gamma(1 + 0.34\mathrm{u_z})} \quad (1)$$

Where ET_0 is the reference evapotranspiration (mm), m is the rate of change of the saturation specific humidity with air temperature (PAK^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), γ is the psychrometric constant (66 PaK^{-1}), T is air temperature (C), u_z is wind speed (m s^{-1}), and δe is vapor pressure deficit (kPa). The output for this equation can then be multiplied by a dimensionless crop coefficient (K_c) to estimate a specific crop evapotranspiration rate (ET_c):

$$\mathrm{ET_c} = \mathrm{K_c}\mathrm{ET_0} \quad (2)$$

These K_c coefficients have been used to estimate ET_c in agriculture (Farg et al., 2012) and forestry (Gurski et al., 2018). However, this single step approach combines crop specific transpiration and E_s effects. If these singular effects are of interest, the dual crop coefficient method may be preferred:

$$\mathrm{ET_c} = (\mathrm{K_{cb}} + \mathrm{K_e})\mathrm{ET_0} \quad (3)$$

Where K_{cb} is the basal crop coefficient that represents a modifier for E_t and K_e is the soil evaporation coefficient. K_e can be estimated using a measure of topsoil moisture and meteorological variables with some efforts to include soil composition (Amazirh et al., 2021). Efforts have been made in agriculture to incorporate K_c coefficients from empirical data in estimation of E_s (Odhiambo and Irmak, 2012; Olivier and Singels, 2012), however, we are unaware of studies that seek to quantify the influence of forest structural characteristics, such as canopy shading, crop residues, and leaf litter on forest K_e and overall K_c.

In this study, we determined E_s under different levels of canopy shade and leaf litter accumulation to explore their individual and combined effects on $E_{s.}$ Because leaf litter accumulation and canopy shading are not directly comparable, we developed a model from our results and existing literature that relates both variables to LAI to further evaluate their relative effects on E_s. Finally, we applied E_s coefficients from our empirical work to management scenarios to predict actual and relative changes in E_s that may occur from common forest management activities. We predicted that both litter accumulation and shade would exhibit negative relationships with E_s, litter accumulation would exert the stronger control, and their combined effects would be dependent. We assumed that our LAI model would represent E_s dynamics during early stand development in that E_s would be high with no shade or litter and would decrease to an equilibrium as modelled LAI increased.

2.2 Materials and Methods

1. Field Site

The experiment was conducted on a flat ridgetop at the Department of Energy's Savannah River Site located in the South Carolina midlands (Aiken, SC, 33°23'15"N.; 81°40'50"W). The site is characterized by the Koppen-Geiger Climate Classification as Cfa, meaning it exhibits a warm temperate climate with fully humid conditions and hot summers (Kottek et al., 2006). The site has a mean annual precipitation of 1035 mm. The soil is described by the NRCS as a Blanton sand with 0 to 6 percent slopes (NRCS, 2010). Detailed sampling of the soil shows an A horizon from 0-13 cm underlain by an E horizon from 13-35 cm. Both horizons have a sand texture and are granular. From 35-110 cm lays a sandy loam transitional (BE) layer. An argillic horizon with sandy clay loam texture and blocky structure is present from 110-230 cm.

A 50 m x 39 m (1950 m^2) plot was delineated for this experiment. The plot was treated with glyphosate in April 2022 and August 2022 to control vegetation. There is a pine-hardwood forest approximately 60 meters south of the southern edge of the plot and a pine forest approximately 175 meters north of the northern edge of the plot.

2. Lysimeters

E_s was measured using aluminum box lysimeters. Seven box lysimeters were installed in the 1950 m^2 plot. The lysimeter is a welded aluminum box that is 90 cm long and 70 cm wide (Figure 1). The bottom of the box is a wedge sloped to a drain with the shallow end x cm from the soil surface and the deep end 75 cm from the soil surface. The lysimeter outlets were welded on laterally at the deepest point of the slope. When the soil was excavated for installation, topsoil was set aside on tarps so that original soil horizons could be approximately maintained. The lysimeter outlet was covered with a stainless-steel mesh and a fabric screen. A layer of pea gravel was spread until the surface of the pea gravel was level. This was followed by a filter cloth across the top of the pea gravel. The lysimeters were then backfilled to their approximate original soil horizons. As backfilling occurred, two volumetric water content (VWC) sensors (Campbell Scientific) were placed in each lysimeter box at 10 cm and 40 cm depth.

The lysimeter outlets were connected to a cylindrical PVC receiver by a short length of reinforced flexible PVC nested inside of a 5cm (2-inch) PVC pipe. The receivers had a diameter of 20.32 cm (8 inches) and a height of 3.05 m buried to a depth of 2.3 m. The receiver was capped on both ends with the bottom cap lined with PVC cement. The connection point was approximately 80 cm below the soil surface and 150 cm above the bottom of the receiver. A concrete collar was formed around the tube below the ground surface to prevent the receiver from floating during high water table events.

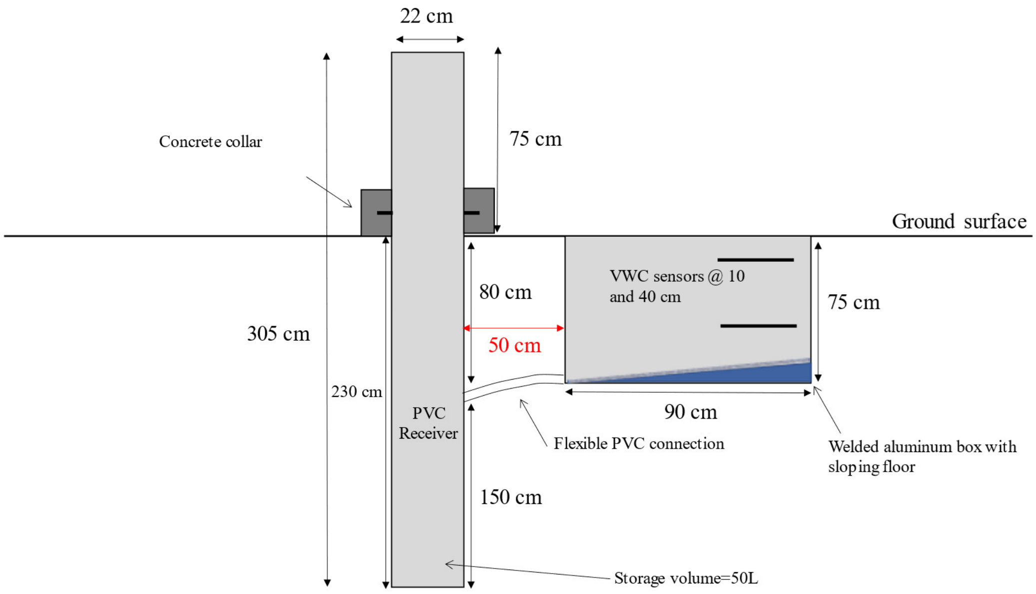

Figure 2.2. A visual diagram for an aluminum box lysimeter

Four T-posts were installed in a 1.8m x 1.2m area surrounding each of the lysimeters. Clear polycarbonate sheets of a similar area were attached to the T-posts and angled to the south. The southern end of the sheet was attached at 15 cm above the soil surface and the northern end of the sheet was attached at 46 cm above the soil surface. The sheets were attached with 20 cm zip ties. When necessary, 1.8m x 1.2m shade cloths were attached directly under the polycarbonate sheets using ball bungees. Chicken wire was cut to the dimensions of the lysimeter surface and was crimped to the edges to cover the surface to ensure that leaf litter stayed on the lysimeter surface.

A simple water balance equation was used to calculate the amount of evaporated water from each of the lysimeters:

$$\mathrm{E_s} = \mathrm{P} - \mathrm{DP} - \mathrm{S} \quad (4)$$

Where E_s is the cumulative soil evaporation (mm) over a 2-3 week period, P is cumulative irrigation (mm) from hand watering, DP is the cumulative amount of deep percolated water (mm), and S is the change in soil water storage (mm) calculated from volumetric water content (VWC, dimensionless) reflectometers (Campbell Scientific).

Lysimeters were watered with backpack sprayers 2-3 times per week with 11.9 liters (18.89 mm) of water to keep lysimeters at a constant, non-water limited state, to estimate P more accurately, and because we used polycarbonate sheets to block incoming precipitation. Water was applied anywhere from 5-10 minutes per lysimeter. The distance from the top edge of the receiver to the water surface inside the receiver, or DP_{T2}, was measured using a well sounder (Solinst) and the following equation was used to calculate DP:

$$\mathrm{DP} = \frac{\pi(3.050 - \mathrm{DP}_{\mathrm{T2}}) * 0.1016^2 * 1000}{0.63} \quad (5)$$

The numerator of equation 6 is the volume of water inside the lysimeter receiver at time T2. 3.050 is the depth of the PVC receiver (m), 0.1016 is the radius of the PVC receiver (m), and 1000 is the conversion factor from m^3 to L. The denominator, 0.63, is the surface area of the lysimeter (m^2). VWC data was sampled every minute and averaged every 15 minutes. These averages were sampled at 8:00:00 on days that infiltrated water was measured. The following equation was used to calculate S:

$$\mathrm{S} = \left(\left(\frac{\mathrm{V40}_{\mathrm{T2}} + \mathrm{V10}_{\mathrm{T2}}}{2} \right) - \left(\frac{\mathrm{V40}_{\mathrm{T1}} + \mathrm{V10}_{\mathrm{T1}}}{2} \right) \right) * 560 \quad (6)$$

Where $V40_{T2}$ and $V10_{T2}$ are VWC averages from the 40 cm and 10 cm sensors at time T2 respectively, and $V40_{T1}$ and $V10_{T1}$ are VWC averages from the 40 cm and 10 cm sensors at time T1 respectively. 560 mm is the average depth of the lysimeter.

3. Weather Station Data

A weather station was installed and recorded temperature (Campbell Scientific), relative humidity (Campbell Scientific), solar radiation (Campbell Scientific), and wind speed (Campbell Scientific) data on a 15-minute interval to a datalogger (Campbell Scientific). These data were used to calculate reference evapotranspiration using the FAO Penman-Monteith method:

$$\mathrm{ET_0} = \frac{0.408\mathrm{m}(\mathrm{R_n} - \mathrm{G}) + \gamma\frac{900}{\mathrm{T}+273}\mathrm{u_z}\delta\mathrm{e}}{\mathrm{m} + \gamma(1 + 0.34\mathrm{u_z})} \quad (7)$$

Where ET_0 is evaporation (mm day^{-1}), R_n is net radiation (MJ m^{-2} day^{-1}), G is soil heat flux (MJ m-^{2} day^{-1}), T is temperature (C), m is the slope of the saturation vapor pressure curve (kPa K^{-1}), γ is the psychrometric constant (=0.0016286 * P_{kPa} L^{-1}) (kPa K^{-1}), u_z is the horizontal wind speed (m s^{-1}), and δe is the vapor pressure deficit (kPa).

4. Experimental Design

In each sampling period, one lysimeter was bare and unshaded and six lysimeters received various litter and shade treatments. The experiment was designed with four levels of each factor (litter and shade) and four replicates of each treatment combination. Shade cloths that block 30%, 60%, and 90% of light penetration were used to emulate levels of canopy shade. We simultaneously measured R_n in open-canopy conditions and under each of our shade treatments to verify that our polycarbonate sheet and shade cloth created shading similar to the 0, 30, 60, and 90% shade we aimed to create over the lysimeters. Regressions of simultaneous data showed that the 90% cloth blocked 90.1% of incoming radiation ($R^2 = 0.99$), the 60% cloth blocked 54.7% of incoming radiation ($R^2 = 0.98$), and the 30% cloth blocked 26.5% of incoming radiation ($R^2 = 0.97$). Loblolly pine leaf litter was dried to a constant mass and deployed in densities of 0, 200, 400, and 800 g m^{-2}. After three weeks, the shade cloths and leaf litter treatments were removed and each lysimeter received a new set of treatments.

The 64 treatments were split into three-week time-periods including six treatments at a time. To compare treatments through time, a relative evaporation rate was needed to eliminate the dimension of time. The ratio of average cumulative E_s from treatment lysimeters and average cumulative E_s from the control lysimeter (referred to as E_{con}) were used to generate a time-specific relative E_s (referred to as E_{rel}):

$$E_{rel} = \frac{E_s}{E_{con}} \quad (8)$$

The linear relationship of average cumulative E_s and cumulative ET_0 were used to generate a K_c coefficient:

$$K_c = \frac{E_s}{ET_0} \quad (9)$$

5. Statistical Analysis

The experiment was designed as a two-way ANOVA with four levels of each factor and four replicates of each treatment combination. Because we only had access to seven lysimeters at one time, replication was achieved through time. Responses of E_{rel} to canopy shade, leaf litter depth, and the interaction of the two variables were analyzed using a factorial ANOVA with lysimeters treated as random effects. A Fisher's LSD test at a 95% confidence interval was used to identify differences between individual treatment means. Linear regressions were performed on relationships between E_s and ET_0 and fit through the origin. The slope of this curve was used to derive treatment-specific K_c coefficients. All analyses were conducted in RStudio and all regressions and graphics were conducted in SigmaPlot.

6. Relating Treatments to LAI

Litter accumulation and canopy shade cannot be compared in quantity, so both variables were converted to LAI. Litter is indirectly related to LAI in that increasing LAI results in increasing leaf litter with some degree of litter decomposition. Shade is directly related to LAI. The two variables were related to LAI by the following: First, LAI by time relationships were used to determine yearly average loblolly LAI from age two to six in four management scenarios (Samuelson et al., 2004), and from age 0 to 5 from another loblolly site (Wright-Osment et al., 2023). Next, time-specific LAI was related to loblolly needlefall rates using the following (Gonzalez-Benecke et al., 2012):

$$\ln(\text{needlefall}) = 0.62455 + 0.97146 * \ln(\text{LAI}) \quad (10)$$

Next, a loblolly decomposition coefficient of 0.33 year^{-1} was used to estimate the mass lost from previous years' needlefall (Sanchez, 2001). LAI was estimated by canopy treatments by the following methods: First, inverse canopy PAR transmittance was related to all-sided LAI using the following (McCrady and Jokela, 1998):

$$\text{Inverse PAR transmittance} = \text{All-sided LAI} * -0.21 \quad (11)$$

All sided LAI was then multiplied by 3.14 to derive one-sided LAI (Will et al., 2005). Derived LAI from litter and shade treatments were then averaged for respective factorial treatments, and an exponential decay regression curve was preformed between E_{rel} and LAI.

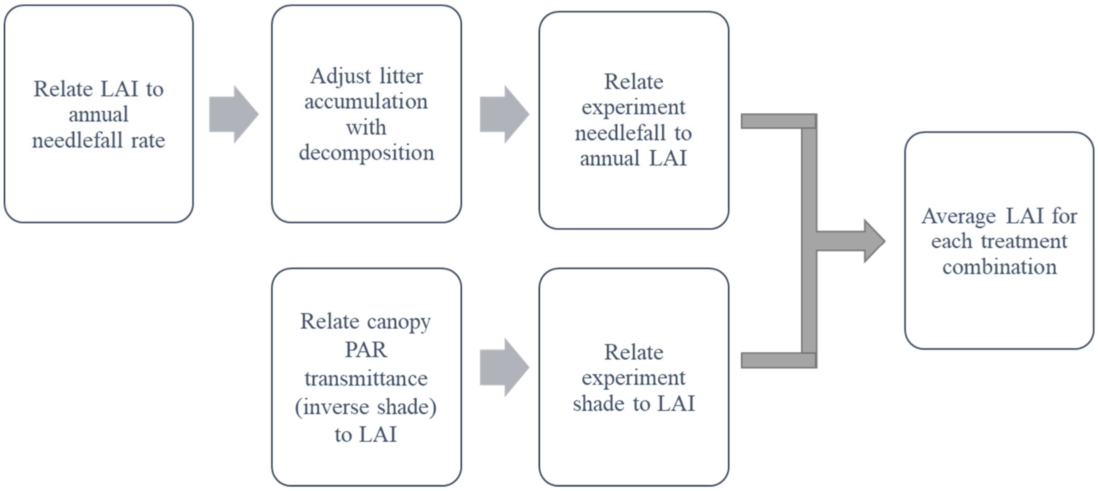

Figure 2.3. Flowchart showing the logical framework for using leaf litter accumulation and canopy shade treatments to model leaf area index (LAI) in this study. PAR is photosynthetically active radiation.

7. Modelling E_s for Forest Management Scenarios

E_s was estimated for three different scenarios using K_c by the following:

$$E_{sp} = K_c * ET_0 \quad (12)$$

Where E_{sp} is the cumulative evaporation for a specific scenario, and where ET_0 was summed for 2022 from the weather station. The three modelled scenarios were a closed canopy forest with 800 g litter m^{-2} and 90% shade, a thinning scenario with 800 g litter

m^{-2} and 60% shade, and a raking scenario with 0 g litter m^{-2} and 90% shade. E_{sp} for the three scenarios were then plotted for comparison.

2.3 Results

Climatic conditions influencing E_s varied substantially across seasons over our observation period, as did modelled ET and measured E_s (Figure 4). VPD ranged from 0.33 to 1.23 kPa with a mean of 0.73 kPa. Cumulative solar radiation ranged from 172 to 512 MJ m^{-2} with a mean of 378 MJ m^{-2}. Modelled daily average ET rates ranged from 1.25 to 4.96 mm day^{-1} with a mean of 3.36 mm day^{-1}. Measured E_s rates ranged from 1.21 to 2.54 mm day^{-1} with a mean of 1.89 mm day^{-1}.

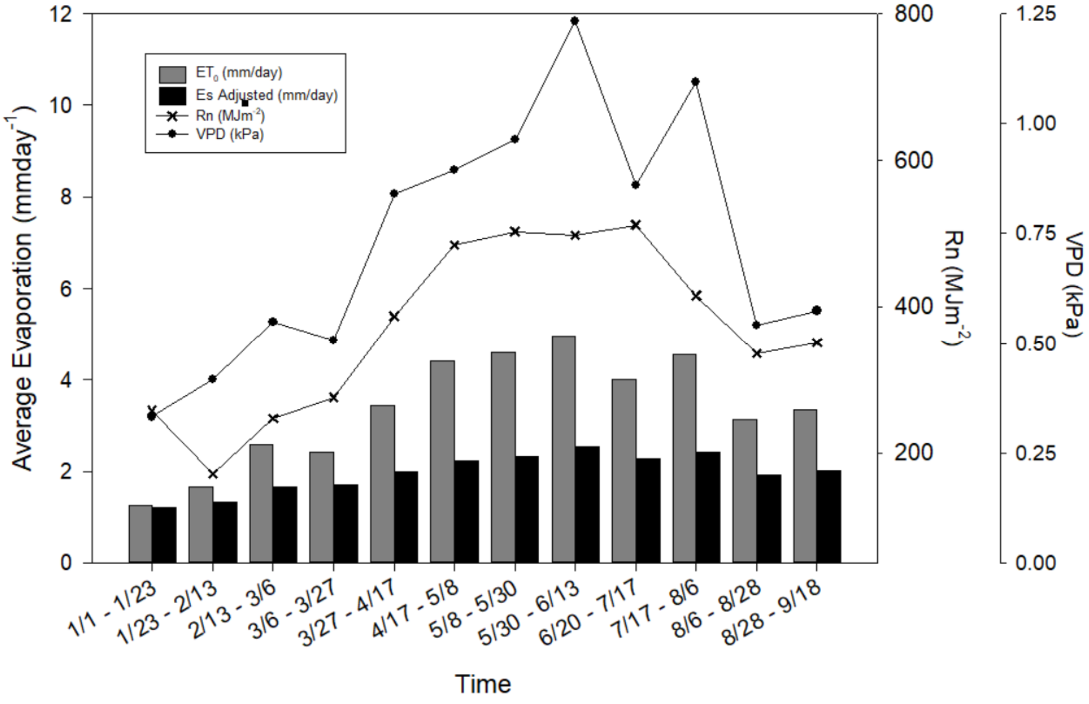

Figure 2.4. Average Penman-Monteith reference evapotranspiration (ET_0), Reference lysimeter evaporation (E_s), vapor pressure deficit (VPD), and cumulative net radiation (R_n) plotted against time in 3 week time intervals.

Measured bare reference E_s was positively related to cumulative ET_0 ($R^2 = 0.98$), cumulative R_n ($R^2 = 0.83$), and average VPD ($R^2 = 0.87$) (Figure 5). Bare reference Es was not related with average wind speed. Measurements of R_n and VPD were used to calculate ET_0 (Equation 8). The ratio of E_s to ET_0 ranged from 0.506 to 0.970 with a mean of 0.627.

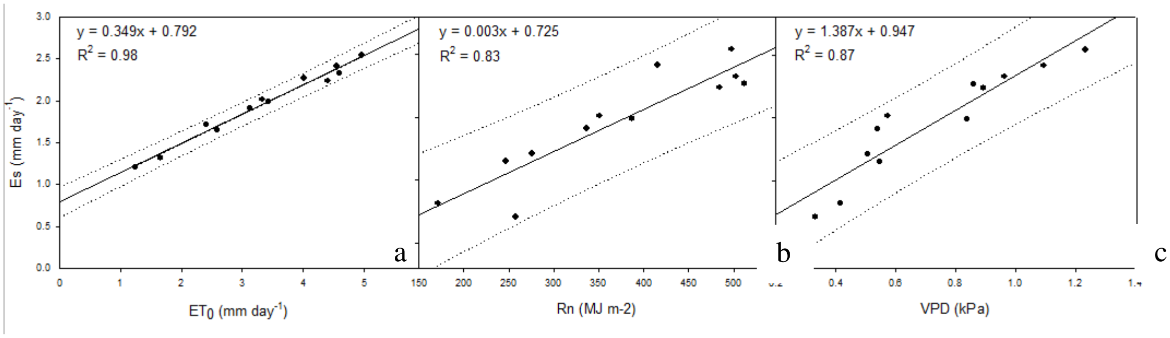

Figure 2.5. The relationship between Penman-Monteith reference evapotranspiration (ET_0) (a), cumulative net radiation (R_n) (b), vapor pressure deficit (VPD) (c), and reference lysimeter evaporation (E_s).

E_{rel} was influenced by litter ($p < 0.001$) and shade ($p < 0.001$), but their effects were independent ($p = 0.206$). Relative to no litter conditions and averaged across all shade treatments, litter accumulation reduced E_{rel} by 27.7%, 52.4%, and 64.1% for the 200 g m^{-2}, 400 g m^{-2}, and 800 g m^{-2} conditions, respectively. Relative to 0% shade conditions and averaged across all litter conditions, shade reduced E_{rel} by 28.7%, 34.8%, and 42.5%, for the 30%, 60%, and 90% shade treatments, respectively. Relative to no litter conditions, and with shade held at 0%, litter accumulation reduced E_{rel} by 24.2%, 55.2%, and 66.7%, for the 200 g m^{-2}, 400 g m^{-2}, and 800 g m^{-2} conditions, respectively.

Relative to 0% shade conditions, and with litter accumulation held at 0 g m^{-2}, increasing shade by 30%, 60%, and 90% reduced E_{rel} by 28.3%, 34.4%, and 45.7%, respectively.

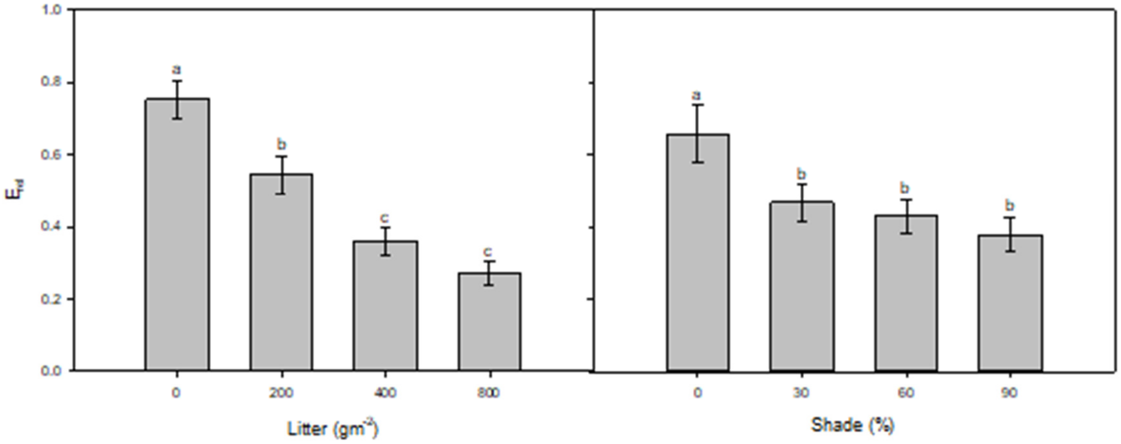

Figure 2.6. Relationship between E_{rel} and litter accumulation averaged across all canopy shade treatments (a) and canopy shade averaged across all litter accumulation treatments (b). Error bars represent one standard error from the mean.

Our LAI model construction predicted that the 0, 200, 400, and 800 g m^{-2} conditions corresponded to LAI values of 0, 0.47, 0.81, and 1.50, respectively and the 0, 30, 60, and 90% shade treatments corresponded to LAI values of 0, 0.40, 0.82, and 1.87 respectively. Our LAI model shows a pattern that is consistent with the notion that E_s is high in no shade and litter conditions and decreases as shade and litter accumulation increase. The exponential decay function fitted to E_{rel} by modelled LAI (R^2=0.76) suggests that there is a saturation effect in which the addition of more modelled LAI does not significantly reduce E_{rel} further (**Figure 2.7**).

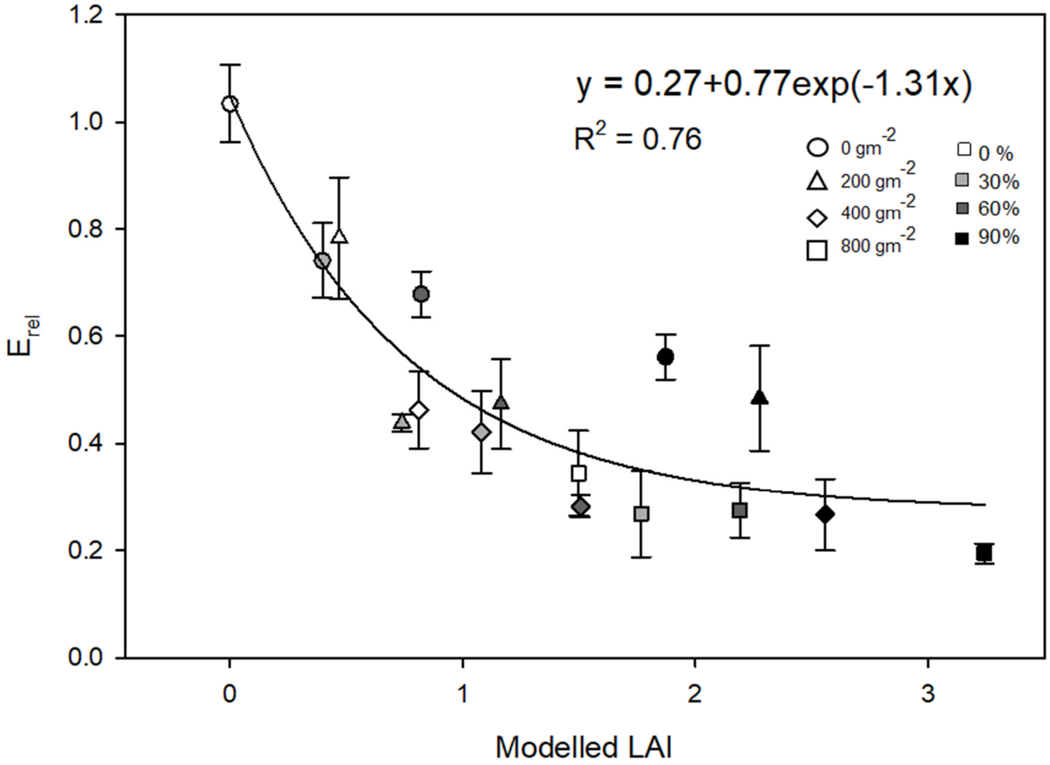

Figure 2.7. E_{rel} plotted against modelled LAI with a fitted exponential decay function.

In general, the slope of the relationship between E_s and ET_0 (K_c) decreased as both litter and shade increased. This relationship generally holds within each level of litter and shade with two exceptions: the transition from 200 g m^{-2} litter to 400 gm^{-2} litter within the 30% shade treatment and the transition from 60% shade to 90% shade within the 200 g litter m^{-2} treatment. Compared to control conditions, treatments reduced Kc within a range of 22% (30% shade, no litter) to 78% (90% shade, 800 g litter m^{-2}). Within the 0% shade condition, litter reduced Kc by 29%, 49%, and 63% for the 200g m^{-2}, 400g

m^{-2}, and 800g m^{-2} conditions respectively.

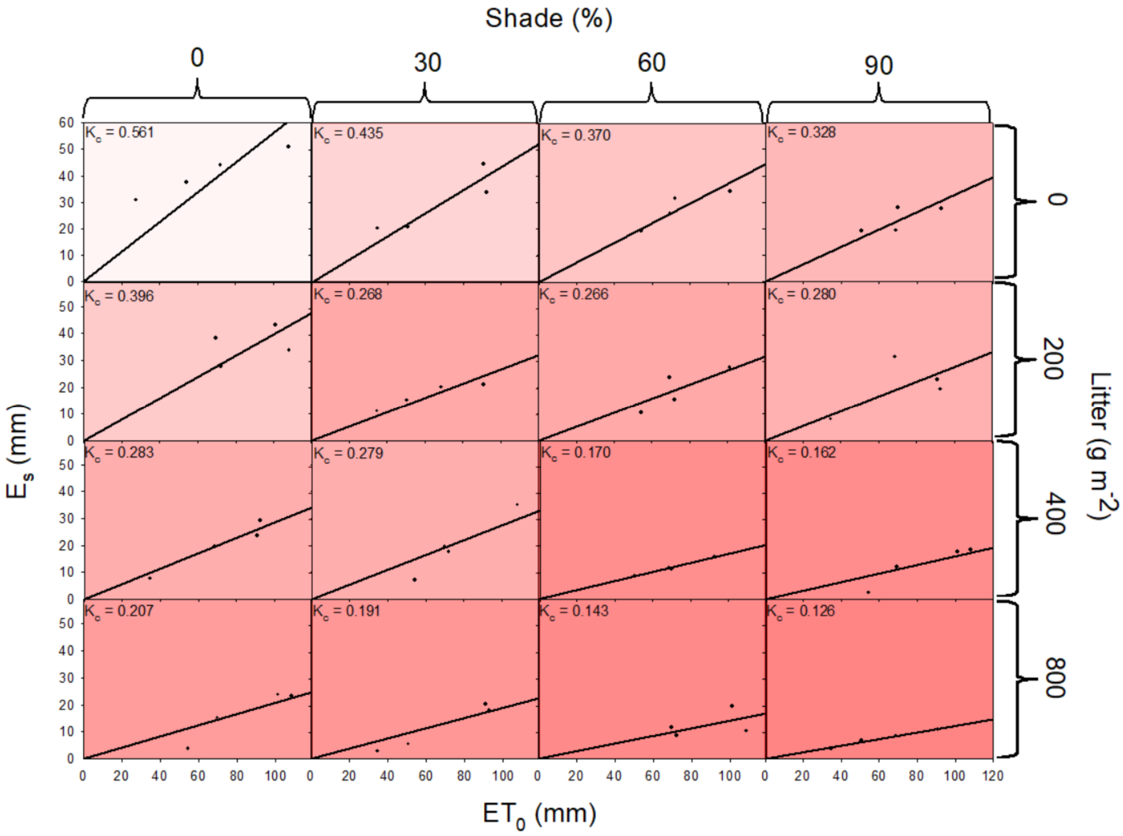

Figure 2.8. Linear regressions of E_s as a function of ET_0 for shade-by-litter treatment combinations. K_c coefficients for each treatment combination are presented in the top left of each regression. Darker shaded squares correspond to a larger K_c value.

Cumulative ET_0 was 1055 mm for the year 2022. The closed canopy ($K_c = 0.126$), thinning ($K_c = 0.143$), and raking ($K_c = 0.328$) forest management scenarios exhibited an annual E_{sp} of 133 mm, 151mm, and 346 mm respectively. Assuming a reduction to the canopy to 60% shade and no removal of late rotation litter, thinning was expected to increase soil evaporation by 13.5% relative to closed canopy conditions. Assuming no reduction to canopy and complete removal of late rotation litter, raking was expected to increase annual soil evaporation by 160.2% relative to closed canopy conditions.

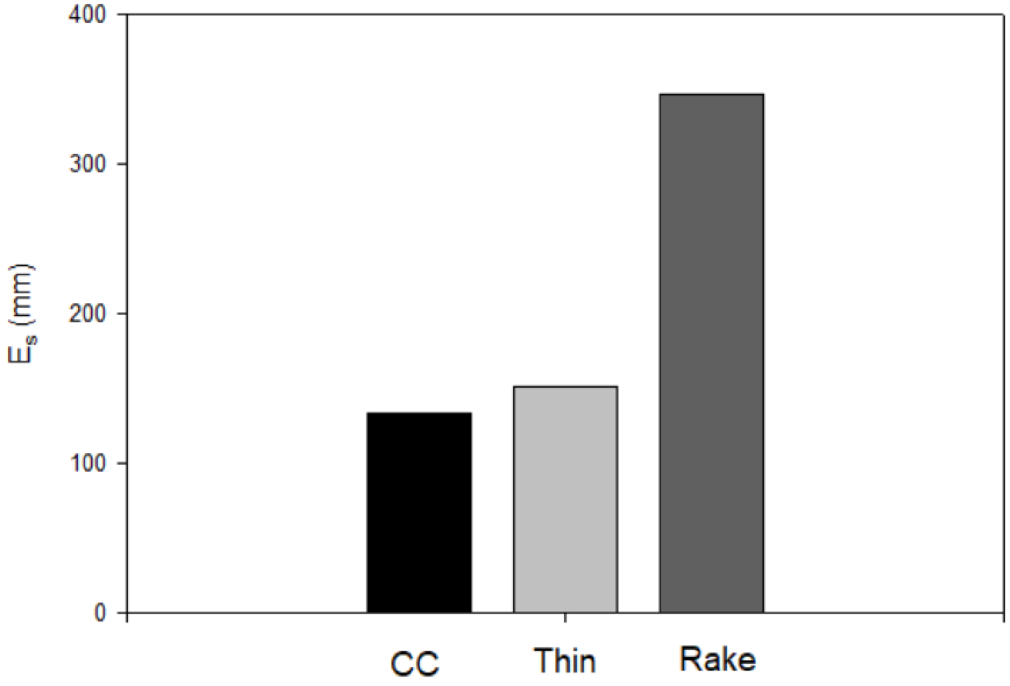

Figure 2.9 Relationships between forest management scenarios and E_{sp} (mm). CC is a closed canopy forest, Thin is a thinning treatment that reduces canopy to 60% with leaf litter at 800 g litter m^{-2}, and Rake is a raking treatment that reduces leaf litter accumulation to 0 g litter m^{-2} with canopy shading at 90%.

2.4 Discussion

Soil evaporation is a complex hydrologic process that can account for a substantial amount of water loss in clearcuts, young forest plantations, and raked forest soils. Our results indicate that environmental factors like R_n and VPD were strong predictors of E_s under bare soil conditions, as was ET_0, with bare E_s accounting for 50 - 97% of ET_0. E_s decreased with increasing shade and litter conditions, and high amounts of litter limited E_s more than high amounts of shade, however, contrary to our prediction, their effects were independent. Our field lysimeter experiment showed that, for varying litter accumulation conditions, E_s was high for bare soil and decreased rapidly to an equilibrium in moderate to high litter conditions. Shade reduced E_s relative to bare soil, but there were no significant differences between low to high shade conditions. Using our modelled LAI – E_s relationship, we showed that, as stands develop and LAI increases, leaf area reduces incident solar radiation on forest soils and leaf litter accumulates and forms a boundary layer separating the soil surface from the atmosphere.

Observed E_s was well correlated with the micrometeorological variables R_n, VPD, and ET_0. Daily average ET_0 was slightly elevated compared to the daily average in a similar physiographic region (Koppen Geiger, Cfa) (Jerszurki et al., 2019), but this may be due to the lack of data in the later months of 2022. In general, E_s from bare soils accounted for a higher proportion of ET_0 in winter months and a progressively lower proportion as evaporative demand increased in the summer months (Figure 4). We attribute this to the lack of transpiring plant material inside the box lysimeters and, because lysimeters were watered at a constant rate throughout the study, the soil may have become water limited in summer months. E_s was related more with ET_0 than with R_n

and VPD (Figure 5). This, in addition to wind speed and temperature inclusion along with R_n and VPD in the model supports the use of ET_0 for ET predictions. However, there is some evidence to suggest that relationship of E_s to ET_0 may vary widely by soil type and texture (Amazirh et al., 2021).

Reduction of E_s under high-shade conditions is consistent, but the behavior of E_s as shade increases to a maximum is variable among studies. We observed that 30% shade reduced E_s 25% compared to the 0% treatment, but these rates were not significantly different from the 60% and 90% treatments. This is similar to results found in a study on semi-arid *Pinus halepensis*, but they found that E_s was close to double in full sun relative to areas with 25% shade (Raz-Yaseef et al., 2010). Other findings in three coffee farms suggest that bare E_s in high shade (60-90%) was reduced by 41% relative to low shade (10-30%) (Lin, 2010). The variation in these results implies that canopy shading may not be a reliable predictor of E_s, canopy cover may not account for soil boundary layer effects such as ground wind speed, and that regional differences in E_s behavior in similar shade conditions could be a result of differences in soil type, soil texture, atmospheric conditions, and/or energetic inputs.

The ability of accumulating litter to substantially decrease E_s is also consistent. As litter amounts increase, E_{rel} and the variation of E_{rel} measurements decrease. This is in support of the notion that litter alters the existing boundary layer of the soil surface by limiting the energetic inputs and increasing the resistance to vapor flux. Our results that 200 g litter m^{-2} thru 800 g litter m^{-2} reduced E_{rel} by 27.7% - 64.1% compared to bare conditions are similar to those of Cui et al. where 600 gm^{-2} thru 1800 g m^{-2} *Pinus tabulaeformis* litter reduced E_s rates by 26.1%-53.8% compared to bare conditions (Cui et al., 2022). They also found that there is a saturation effect in which the addition of more litter after 1200g m^{-2} no longer reduced E_s rates. One key difference between this and the present study is that their bare soil conditions included a canopy that blocked 70%-90% of incoming solar radiation. The similarities in E_s behavior and reduction range of these two studies despite Ciu et al. deploying litter treatments of more than double that of this study are interesting and may suggest that if shading conditions are already high, the ability for lower litter accumulation amounts to limit soil evaporation from bare soil may be suppressed. This implies that there may be an interacting effect of litter accumulation and canopy shade, however, our statistical analysis did not yield a significant effect of the interaction.

High amounts of litter accumulation were more effective than shade in limiting E_{rel}, confirming results found in several systems (Cui et al., 2022; 2017; Villegas et al., 2010). Our lowest litter accumulation (200gm^{-2}) treatment did not reduce E_{rel} more than our lowest shade (30%) treatment, but our lowest two litter accumulation treatments did. Contrary to our expectations, and despite the ability of increasing litter to alter the soil's existing boundary layer, there was no interaction between shading and litter accumulation.

Exploration of E_s patterns over changes in LAI are documented in agriculture and agroforestry but are not well studied in forestry. A relationship between LAI and E_s in wheat and corn showed that E_t and E_s were approximately equal at LAI values of 0.2-0.3, and, for corn, E_s was reduced to and equilibrated at approximately 10% of total ET at an LAI value of 2.0 (Merta et al., 2006). For winter wheat, E_s was reduced to below 4% of total ET at an LAI value of 1.5 (Merta et al., 2006). In a maize/oak agroforestry system, reducing LAI from 2.5 to approximately 0.25 by pruning trees resulted in an increase of E_s from approximately 70% of bare E_s to approximately 90% (Jackson and Wallace, 1999). It is important to note that the above studies have no mention of the litter or crop residue characteristics of the field sites. We are unaware of forest studies that seek to directly compare LAI to empirical E_s through early development, however, Di et al. found strong inverse exponential relationships between K_e (estimated as the ratio of Es to ET_0) and canopy LAI in a *Populus tomentosa* plantation (Di et al., 2019). Our modelled LAI – E_{rel} relationship suggests that relative evaporation starts out at 80% to 100% in bare soil and in low canopy and litter conditions when typical LAI is between 0 and approximately 0.5 and equilibrates at approximately 30% when typical LAI is around 1.5. However, there are some deviations from this relationship. Even if high amounts of LAI are predicted by high shade (90%, for example) with no litter accumulation, only moderate reductions in E_{rel} are maintained (See Figure 7). In a forest, this would mean that canopy LAI without some quantitative measure of leaf litter accumulation may not accurately predict E_s.

K_c regressions show that average daily E_s was reduced by 44% relative to average daily ET_0 for bare conditions, corroborating data from a similar physiographic region. (Gava et al., 2013). However, in this experiment, E_s was reduced more as litter accumulation increased. For example, Gava et al. reported a reduction of 59% relative to ET_0 for a wheat crop residue accumulation of 10 $Mgha^{-1}$ (907 gm^{-2}) while we found a reduction of 79% for loblolly litter accumulation of $800gm^{-2}$. K_c decreased more gradually while shade percentage increased, than while litter accumulation increased.

This is consistent with our finding that litter accumulation affected E_s more than canopy shade.

Minimizing E_s may be desirable because the flux does not contribute to forest growth and represents a portion of soil water that could be available for Et, so understanding how management influences E_s can be used to better understand management implications. Pre-commercial thinning and pine straw raking are two common management techniques applied in southern pine forests. By applying our K_c coefficients to cumulative ET_0, we can predict E_s outcomes if thinning and/or raking occurs. We found that a thinning scenario predicted a small increase in annual E_s relative to closed canopy conditions, while a raking scenario predicted an increase in annual E_s of over double that of closed canopy conditions. It is worth noting that the key assumptions of using these coefficients to predict annual E_s are that the leaf litter accumulation and canopy shading are homogenous through space in the area of interest, and that they do not change over the year. Because forest controls are dynamic and variable through space, these assumptions are likely often violated, however, our coefficients provide a valuable tool for assessing the hydrologic implications for the employment of forest management strategies.

2.5 Conclusions

In summary, litter accumulation exerted a stronger control on E_s than canopy shade. We present three evidences in support of this claim: 1) our lowest litter accumulation (200gm^{-2}) treatment did not reduce E_{rel} more than our lowest shade (30%) treatment, but our highest two litter accumulation treatments reduced E_{rel} more than any shade, 2) high shade treatments corresponded to high modelled LAI values, but in the absence of litter and in low litter conditions, E_s was higher than other treatments of similar modelled LAI, and 3) K_c coefficients were reduced more as litter increased than as shade increased. We also found that observed patterns of E_{rel} are well explained by modelled LAI (R^2=0.76) with leaf litter incorporation and this pattern is reflective of forest dynamics through time. Finally, we showed that the application of modelling approaches to forest dynamics may inform E_s trends given different forest management scenarios.

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CHAPTER 3: CONCLUSION

This thesis was driven by gaps in research on the effects of forests on the dynamics of soil evaporation through stand development. We focused on the effects of canopy shading (increases in LAI), and leaf litter accumulation because these are most likely to limit soil evaporation in real forests, and these can be manipulated using forest management strategies to optimize hydrologic dynamics for specific needs.

Our first objective was to determine the relative amounts that canopy shading and litter accumulation were able to limit soil evaporation. We found that, when averaged across all shade treatments, litter reduced evaporation from bare conditions by 27.7%, 52.4%, and 64.1% for the 200 g m-2, 400 g m-2, and 800 g m-2 conditions, respectively, and, when averaged across all litter conditions, shade reduced evaporation from bare conditions by 28.7%, 34.8%, and 42.5%, for the 30%, 60%, and 90% shade treatments, respectively. Our second objective was to relate our litter accumulation and canopy shade treatment values to modelled LAI to explain the trend of our empirical evaporation through the lens of the dynamics of forest stand development. We found that modelled soil evaporation was well explained by LAI (R^2=0.76) but, generally, soil evaporation estimations were high in conditions where high LAI was modelled by high canopy and low to no leaf litter. Our final objective was to suggest soil evaporation K_c coefficients for varying leaf litter - canopy shade scenarios. We showed that our K_c coefficients can be applied to forest management scenarios in which litter accumulation and shading are manipulated.

We believe that, regardless of desired hydrologic outcomes, our results can be used to understand the effects of growing forests on soil evaporation, and to inform better forest management strategies in the future.

APPENDIX

TIME	LAI	NF	NFD
2	0.79665	160.3	153.225
3	2.360825	643.3691	466.4
4	3.3291	957.3106	694.075
5	3.174175	943.4937	666.725
6	3.661675	1035.39	752.925

Table A.1 Average Leaf Area Index (LAI) relationship with time (Samuelson et al., 2004; Wright-Osment et al., 2023), needlefall (NF) (Gonzalez-Benecke et al., 2012), and needlefall with a decomposition coefficient (Sanchez, 2001) included (NFD).

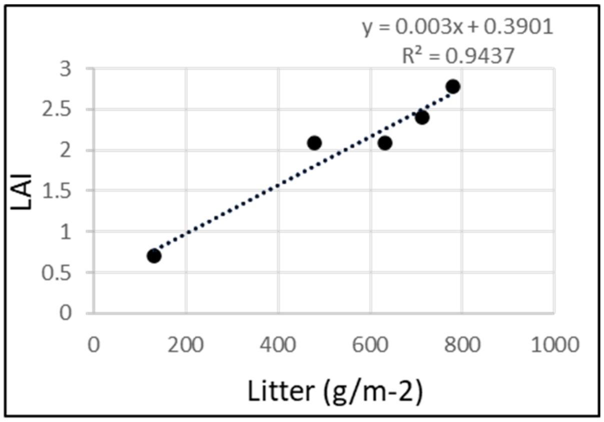

Figure A.1 Linear relationship between Average LAI and needlefall with a decomposition coefficient included (**Table A.1**).

	DF	Sum of Squares	Mean Squares	P-Value
Canopy	3	0.7121	0.2374	$3.31*10^{-6}$
Litter	3	2.2020	0.7340	$6.34*10^{-13}$
Canopy*Litter	9	0.2404	0.0267	0.206
Residuals	48	0.9026	0.0188	

Table A.2. ANOVA table including effects of shade, litter, and the interaction of shade and litter on E_{rel}