



Improved Descriptions of Herbaceous Perennial Growth and Residue Creation for RUSLE2

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ABSTRACT

Earlier versions of the Revised Universal Soil Loss Equation, version 2 (RUSLE2) calculated vegetative residue production only during periods of canopy decline or in response to management operations. This resulted in underestimation of residue amounts and overestimation of soil erosion from pasture and hay lands. To solve this problem, new vegetation routines were implemented in RUSLE2. These modifications were designed to better reflect the amount of residue added by perennial vegetation during its growth and to make it easier to model haying and grazing scenarios. The new routines were based on the assumption that all unharvested aboveground biomass growth will die after its life span is reached, and this biomass will be added to a standing residue pool. Trained specialists can define the characteristics of a vegetation assemblage in terms of total annual potential production under good management, monthly production percentages reflecting expected fertility and irrigation levels, average vegetation lifespan, maximum canopy height, cutting height for optimal yield, and the tendency of the vegetation to thicken at lower heights (form a sod) in response to repeated defoliations. Users will specify actual harvest management and an underlying model predicts plant growth responses in terms of the amount of harvested forage and the amount of above- and belowground residues returned to the soil. The USDA-NRCS is developing extensive databases so that the new version of RUSLE2 will allow erosion estimates to be a factor considered as part of forage and grazing planning.

RUSLE2 IS A conservation planning tool that predicts soil erosion and sediment delivery from hillslopes based on climate, soil, topographic, and management conditions described by the user. Vegetation descriptions used in RUSLE2 are generally developed by a discipline expert based on growth characteristics for a specific geographical area. Vegetation growth is not dynamically linked to climate, but RUSLE2 tracks climate-linked decomposition of multiple classes of plant residues on a daily time step. Residue cover and amounts of plant biomass in the soil greatly influence RUSLE2 erosion estimates.

Management descriptions in RUSLE2 comprise combinations of field operations and vegetations. Field operations are typically tillage, planting, and harvest or grazing events that occur on particular dates and that affect the land surface by creating roughness, adding or removing biomass, mixing residues into the soil, or starting or ending vegetation growth. Vegetation descriptions specify temporal growth patterns, the canopy cover, height, and shape, harvest biomass relationships, hydraulic roughness properties, and associated residue characteristics for a single species or a mixture of species. RUSLE2 uses the information contained in the vegetation description to determine its effect on erosion factors (L , C , and P) through numerous variables tracked or calculated internally by

RUSLE2, including plant residue biomass in the soil (termed *soil biomass* in RUSLE2), surface residue cover, surface roughness, canopy cover, Manning's roughness, and the runoff curve number (Renard et al., 2011).

In RUSLE (Renard et al., 1997), earlier versions of the RUSLE2 (USDA-ARS, 2008), and several other erosion models (EPIC, Williams et al., 1989; WEPP, Arnold et al., 1995; WEPS, USDA-ARS, 2006; APEX, Williams et al., 2008), residue production is assumed to occur only during crop senescence or when a crop is harvested or killed. Estimating residue creation directly from the decline in live biomass, as in prior versions of RUSLE2, is equivalent to assuming that there is no residue production during periods of increasing aboveground biomass and no net primary productivity (NPP, defined as gross photosynthesis minus plant respiration per unit ground area) after peak biomass is reached. Under these assumptions, NPP can be approximated as the increase in live biomass, and, if there is no harvest, total NPP is approximated by the peak standing crop of biomass (Lauenroth et al., 2006). These are probably acceptable assumptions for the aboveground biomass of many annual crops, but in mixed grasslands different components mature at different times during the year and tissue turnover occurs continually (Parsons et al., 1983), so residue creation is mistimed or underestimated if only such end-of-season senescence is considered. Even with annual crops, turnover of roots contributes to rhizodeposition, which is a significant sink of NPP C (Johnson et al., 2006). For the erosion-estimation role of RUSLE2, underestimation of plant residue and soil biomass creation leads to significant overestimation of soil erosion.

The style of vegetation descriptions used previously in RUSLE2 has also made it difficult to model perennial vegetation with repeated cuttings or grazing. Previous RUSLE2

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Abbreviations: NPP, net primary productivity.

technology required that management descriptions be built by piecing together several vegetation descriptions, each representing brief periods of growth, including modeling regrowth following each harvest operation. Also, earlier RUSLE2 procedures created standing residue only when a crop was killed because senescent declines in aboveground biomass were assumed to directly become surface residue (Table 1).

To overcome these limitations, new procedures described here were developed and implemented in RUSLE2 (<http://www.ars.usda.gov/Research/docs.htm?docid=20222>). Users describe vegetation growth characteristics in terms of the total expected yield under optimal management, fractions of growth occurring each month, maximum expected canopy height, and the optimum cutting height for maximum forage yield. RUSLE2 then calculates the parameter values needed to drive an underlying growth model, which defines any new growth on each day. In the absence of forage harvest or biomass removal, the daily change in live biomass amount is calculated as the difference between new growth and the death of old growth. After its lifespan is reached, live biomass that is not harvested is added to a dead biomass pool (Table 1). Daily changes in residue biomass result from the difference between death and decomposition or residue harvest. Growth patterns and residue creation are dynamically altered in RUSLE2 in response to management operations involving biomass removal or changes in declared yield levels. A new RUSLE2 perennial vegetation field operation harvest process was also created to facilitate descriptions of biomass removal through operations like

grazing, haying, or burning and how losses from such operations are added as residues to the soil surface.

RUSLE2's new routines simplify the creation of vegetation and management descriptions for perennial systems and provide more realistic estimates of residue creation and soil erosion for pastures, hay fields, and other systems dominated by perennial herbaceous vegetation. Our objective was to document the underlying crop growth and residue creation model. Details of the new RUSLE2 biomass field operation harvest process and associated new interface tools will be reported elsewhere.

VEGETATION GROWTH MODEL

Vegetation Growth

RUSLE2 has adopted simplified procedures based on the concepts of plant growth presented by Schwinning and Parsons (1996) and Thornley (1998). Conceptually, biomass is separated into *structure* (leaves, stems, and roots) and *substrate* (labile material that we loosely call *carbohydrate substrate*):

$$B = B_x + B_C \quad [1]$$

where B is the total biomass, B_x is the structure, and B_C is the carbohydrate substrate (all kg ha^{-1}). According to this approach, growth depends on the total amounts of both structure and substrate and on the ratio of these.

Ignoring root/shoot partitioning, Schwinning and Parsons (1996) described photosynthetic "assimilation" of biomass (NPP) as depending on the amount of structure (a surrogate for leaf area) by

$$\frac{dB}{dt} = a \frac{B_x}{B_x + K_B} \quad [2]$$

The "photosynthetic assimilation rate" dB/dt ($\text{kg ha}^{-1} \text{d}^{-1}$) is proportional to the coefficient a (the maximum assimilation rate at very large biomass, $\text{kg ha}^{-1} \text{d}^{-1}$), the standing structural biomass B_x , and the constant K_B (kg ha^{-1}), defined as the structural biomass that gives half of the maximal NPP.

The growth of structure is then proportional to the amount of structure (leaf area) and the ratio of carbohydrate substrate to structure in the biomass (Schwinning and Parsons, 1996):

$$\frac{dB_x}{dt} = g B_x \frac{B_C/B_x}{(B_C/B_x) + K_C} \quad [3]$$

where the coefficient g (d^{-1}) is an intrinsic species-specific growth rate parameter and the constant K_C is the carbohydrate/structure ratio for which the growth rate per unit structure is half of the maximum, given by Schwinning and Parsons (1996) as $\sim 1.2 \text{ kg } B_C \text{ kg}^{-1} B_x$. Combining Eq. [1–3], growth depends on the adequacy of the substrate to support the quantity of structure. If the substrate is small, all biomass creation goes into substrate rather than structure. If both substrate and structure are substantial, the growth of structure (birth) may exceed the photosynthetic assimilation rate, in which case carbohydrate substrate levels will decline.

Thornley (1998) showed that more stable simulations resulted if assimilation is reduced when there is not a sink for available photosynthate (feedback inhibition), so that substrate

Table 1. Comparison of conventions used to describe the interaction of live biomass pools and residue pools in traditional and new vegetation procedures.

Situation or operation	Old RUSLE2 vegetation procedures	New RUSLE2 vegetation procedures
Decline in aboveground biomass	aboveground biomass loss is added to surface residue pool	aboveground biomass is converted to standing residue when its lifespan is reached
Decline in root biomass	decline if root biomass is added to root residue pool	added to active and woody residue pools after lifespan is reached
Kill crop (shoots)	converts live aboveground biomass to standing residue	converts live aboveground biomass to standing residue
Kill crop (roots)	converts live roots to the root residue pool	converts live roots to the active and woody root residue pools
Flatten standing residue	converts standing residue to surface residue	converts standing residue to surface residue
Standing residue decomposition	decays at a fraction of the rate used for surface or buried residues and is converted to surface residue as a function of decomposition controlled by climate and residue properties	decays at a fraction of the rate used for surface or buried residues and is converted to surface residue as a function of decomposition controlled by climate and residue properties
Surface residue decomposition	up to 25% of amount lost is added to the buried residue pool in the upper 50 mm of the soil	up to 25% of amount lost is added to the buried residue pool in the upper 50 mm of the soil

does not accumulate to high levels. In this case, Eq. [2] may be modified as

$$\frac{dB}{dt} = a \frac{B_x}{(B_x + K_B) \left\{ 1 + \left[(B_C/B_x) / J \right] \right\}} \quad [4]$$

where the additional term in the denominator reduces assimilation when the ratio of substrate to structure exceeds J , given by Thornley (1998) as $0.1 \text{ kg } B_C \text{ kg}^{-1} B_x$. To disable this substrate birth inhibition, a large number may be assigned to J . Note that both J in Eq. [4] and K_C in Eq. [3] relate to the B_C/B_x ratio, which is approximately the carbohydrate substrate concentration in the biomass if $B_x \gg B_C$.

While Schwinning and Parsons (1996) dynamically linked growth to the measured solar radiation, water stress, and available nutrient levels, in RUSLE2 users must describe the amount and timing of growth of the vegetation community, taking ambient climate and fertility conditions into consideration. The user is asked to specify parameters that are relatively easy to understand—specifically the monthly portions of growth and the total amount of forage typically produced. RUSLE2 uses those inputs to determine the time-varying a values in Eq. [4] needed to create the desired growth patterns. The growth patterns and yield levels selected by the user must reflect climate (day length, light, temperature, water), genetic (species mixture), irrigation, and fertility effects.

Root/Shoot Growth Partitioning

To define root growth, the new perennial vegetation routines consider the ratio of the full depth of live roots to the total live aboveground biomass and specify this as the root/shoot ratio RS^* . These values reflect a range of species, climates, and fertility conditions. As described in USDA-ARS (2008, Section 9.2.1), RUSLE2 assumes that 61% of the total root biomass is found in the top 10 cm of the soil, so the total roots determined by the new perennial vegetation routines can readily be converted to the roots in the top 10 cm by multiplying the total live roots by 0.61. Equations [1–4], which lump both shoots and roots into “structure,” were modified to separately predict shoot and root growth. The development assumes that new structure growth is proportional to the ratio of total substrate to shoot structure and that this growth is apportioned between shoots and roots in a way that returns the plant toward a target root/shoot ratio. Because several researchers, including Crider (1955), have reported that root growth stops abruptly after severe defoliation, we assumed that, following defoliation, most NPP goes to shoot structure and that the root/shoot ratio will gradually approach RS^* as growth continues with time.

Equation [1] then becomes

$$B = B_{x,s} + B_{x,r} + B_C \quad [5]$$

where $B_{x,s}$ refers to shoot structure and $B_{x,r}$ refers to root structure.

From Eq. [3], total growth becomes

$$\frac{dB_x}{dt} = g B_{x,s} \frac{C}{C + K_C} \quad [6]$$

where $C = B_C/B_{x,s}$ is the ratio of carbohydrate substrate to shoot structure.

Growth is apportioned between shoots and roots based on two dimensionless coefficients, λ_s and λ_r , representing the fraction of mass in shoots and roots, respectively, as

$$1 = \lambda_s + \lambda_r \quad [7]$$

At any time, the ratio of root to shoot structure, $B_{x,r}/B_{x,s} = RS$, can be compared with the target ratio RS^* . The target fraction of total structure that is shoots (T_s) is given by

$$\frac{1}{1 + RS^*} = T_s \quad [8]$$

while the current shoot fraction S_F is

$$\frac{B_{x,s}}{B_{x,s} + B_{x,r}} = S_F \quad [9]$$

The equilibrium partitioning of new structure between shoots and roots that will give the target RS^* depends on several parameters: the shoot lifespan, l_s (d), the active root lifespan, l_{r1} (d), the woody root lifespan, l_{r2} (d), and the fraction of active roots that become woody roots, f . The target fraction of shoot structure, λ_s^* , may then be calculated as

$$\lambda_s^* = \frac{l_{r1} + f l_{r2}}{RS^* l_s + l_{r1} + f l_{r2}} \quad [10]$$

The fraction of structure growth that goes to shoots is determined based on the relative values of S_F and T_s :

$$\begin{aligned} \text{if } \frac{S_F}{T_s} < 1, \text{ then } \lambda_s &= 1 - \frac{S_F}{T_s} (1 - \lambda_s^*) \\ \text{if } \frac{S_F}{T_s} \geq 1, \text{ then } \lambda_s &= \lambda_s^* \\ \lambda_r &= 1 - \lambda_s \end{aligned} \quad [11]$$

These relationships cause shoots to be produced at the expense of new roots immediately after defoliation, with the roots catching up later, resulting in the root/shoot ratio eventually approaching the target.

Finally, shoot, root, and carbohydrate substrate changes are calculated by

$$\frac{dB_{x,s}}{dt} = \lambda_s \frac{dB_x}{dt} = \lambda_s g B_{x,s} \frac{C}{C + K_C} \quad [12]$$

$$\frac{dB_{x,r}}{dt} = (1 - \lambda_s) \frac{dB_x}{dt} \quad [13]$$

$$\frac{dB_C}{dt} = \frac{dB}{dt} - \frac{dB_x}{dt} \quad [14]$$

where photosynthetic assimilation is calculated from a modification of Eq. [4] based only on shoot structure:

$$\frac{dB}{dt} = a \frac{B_{x,s}}{(B_{x,s} + K_B) [1 + (C/J)]} \quad [15]$$

Implementation and User-Specified Inputs

The relationship between the current ideal birth rate and NPP in the forgoing plant growth model is through the parameter a in Eq. [15]. Whereas a in the model of Schwinning and Parsons (1996) was a constant that reflected the efficiency of use of photosynthetically active radiation, in the RUSLE2 radiation is not an input and a is varied on a daily basis to reflect the growth pattern defined by trained vegetation database developers. These developers specify monthly input values of: (i) the percentage of NPP, NPP_m , (ii) the effective lifespan (d) of the shoot biomass produced, (iii) the target ratio of root biomass to shoot biomass, (iv) the fraction of active roots that are transformed into woody roots after their active lifespan has been reached, and (v) the “death to external” percentage of live aboveground biomass that does not become standing residue following shoot death. The developers also specify annual average values of: (i) the total annual forage production target under optimal management, (ii) the life span of “active roots,” (iii) the life span of “woody roots,” (iv) the maximum canopy height achieved at maturity (not the inflorescence height), H_{max} , and (v) the optimal height at which the vegetation should be cut under management to produce the most forage, H_p , dubbed the *potential cut height*.

The shoot lifespan values selected implicitly reflect senescence respiration (Díaz-Solis et al., 2003). A “death to external” parameter can be used to reduce the fraction of live aboveground biomass that becomes standing dead residue on death. This parameter may be used to limit the accumulation of residue biomass when biomass is translocated to storage organs

or woody structure, which are not explicitly modeled in the current herbage model. With the default “death to external” value (0.0, Table 2), 100% of the live biomass is transferred to standing residue on reaching its lifespan. Similar amounts of residue biomass can be created using a longer lifespan combined with a smaller “death to external,” as with a shorter lifespan and a greater loss to external value. Unlike other parameters specified with monthly values, this parameter does not affect a biomass pool or biomass partitioning during growth. Rather, the disaggregated daily values of “loss to external” are applied on the day when the vegetation in any pool dies.

RUSLE2 assumes a linear relationship between canopy height and live aboveground biomass, with a zero intercept. As described below, the slope of this line may be modified under repeated harvests of sod-forming grasses. Because of the linear relationship, however, on any given day the fraction of canopy height removed by a harvest operation is equal to the fraction of biomass removed.

With a daily time step, Eq. [15] is represented in finite difference form as

$$\frac{dB_{(i)}}{dt} = a_{(i)} \frac{B_{x,s(i-1)}}{[B_{x,s(i-1)} + K_B] C_{2(i)}} \quad [16]$$

$$C_{2(i)} = 1 + \frac{C_{(i-1)}}{J}$$

where (i) and $(i - 1)$ represent the values for the current and previous time steps, respectively. This leads to the relationships

$$\frac{dB_{x(i)}}{dt} = gB_{x,s(i-1)} \frac{C_{(i-1)}}{C_{(i-1)} + K_C} \quad [17]$$

$$\frac{dB_{C(i)}}{dt} = \frac{dB_{(i)}}{dt} - \frac{dB_{x(i)}}{dt} \quad [18]$$

Table 2. Description of variable names, symbols, and default values used in the RUSLE2 vegetation model.

RUSLE2 variable	Default value	Definition
<u>Vegetation growth model</u>		
MODVEG_IDEAL_NET_PROD_POT, kg ha ⁻¹ d ⁻¹ (a)		daily coefficients calculated internally to reflect user-specified monthly growth percentages, target net primary productivity (NPP), and location; used in Eq. [15]
MODVEG_IDEAL_GROWTH_KB, kg ha ⁻¹ (K_B)	170	shoot structural biomass that gives half or maximum NPP, used in Eq. [15] (normally hidden from user)
MODVEG_G, d ⁻¹ (g)	0.6	intrinsic growth rate parameter; used in Eq. [12] (normally hidden from user)
MODVEG_IDEAL_GROWTH_KC (K_C)	1.2	ratio of carbohydrate substrate to structure, where growth rate per unit structure is half maximum; used in Eq. [12] (normally hidden from user)
MODVEG_J (J)	0.2	coefficient to reduce birth considering the ratio of substrate to structure; used in Eq. [7] (normally hidden from user)
VEG_PERENN_ASSUMED_FORAGE_BIOMASS, kg ha ⁻¹	1500	arbitrary total biomass value above which daily growth is summed to determine the annual potential forage harvest target
LATITUDE, °	35	latitude ($S < 0$) of assumed location of vegetation growth, used in production limit calculations
VEG_PERENN_PROD_LIMIT_MULT	6	limit on a equal to x times the largest daily potential forage amount, also varies with location solar isolation curve (normally hidden from user)

Table 2. Continued.

RUSLE2 variable	Default value	Definition
MODVEG_MULT_SENS_FACTOR	10	factor used in transforming monthly values into smoothly varying daily disaggregated growth values (normally hidden from user)
MODVEG_LIFESPAN_SPREAD_PORTION, %	40	percentage of the lifespan that reflects the width of the triangular distribution of life spans (normally hidden from user)
MODVEG_PLATEAU_POT_LIVE_BIOMASS, kg ha ⁻¹		model-calculated aboveground live biomass at potential cut height to get full site NPP
VEG_PERENN_ANNUAL_POT_FORAGE_PROD, Mg ha ⁻¹ yr ⁻¹		model-calculated "potential" forage yield resulting from estimated NPP and daily harvest of material above potential cut height
<u>Annual or single-valued user inputs</u>		
PERENN_VEG_TYPE	perennial	either annual or perennial (no woody roots created for annuals)
VEG_PERENN_ANNUAL_PROD, Mg ha ⁻¹ yr ⁻¹ (NPP _T)		user-specified target of total annual NPP
VEG_PERENN_MAX_CANOPY, %	70	maximum canopy cover at maturity
MODVEG_MAX_BIOMASS_HT, cm (H _{max})	46	user-specified vegetation full canopy height if uncut (not maximum inflorescence height)
MODVEG_POT_FORAGE_CUT_HT_ABS, cm (H _p)	7.6	cutting height for optimal management (used to determine "potential" forage yield)
MODVEG_CARB_EFFECT_PORTION_MAX_HT, %	100	portion of current maximum height where storage carbohydrate is found (default = uniform distribution throughout aboveground structure)
MODVEG_ENV_MIDPT_PORTION, fraction (h _m)	0.5	fraction of maximum biomass resulting from repeatedly cutting at half of H _{max} (=0.5 if not sod forming)
VEG_MODVEG_DAYS_CUT_INTERVAL_MORE_LEGGY, d (D _L)	7	days after a single cutting of a sod-forming herbage before the target ray height exceeds the value at the time of cutting
VEG_MODVEG_DAYS_FOR_HT_ADJUST, d (D _m)	90	days needed for full adjustment of sod-forming herbage
VEG_PERENN_ACTIVE_ROOTS_LIFESPAN, d (l _{r1})	45	average lifespan value of active root biomass
VEG_PERENN_WOODY_ROOTS_LIFESPAN, d (l _{r2})	300	average lifespan value of woody root biomass
RES_ACTIVE_ROOTS_RES_DECOMP_HALF_LIFE, d ⁻¹	10	decomposition half-life of active root residues under optimal conditions
RES_WOODY_ROOTS_RES_DECOMP_HALF_LIFE, d ⁻¹	50	decomposition half-life of woody root residues under optimal conditions
MODVEG_MIN_SHADING_ADJUST_PORTION, % (D _{min,p})	50	maximum percentage of daily NPP despite shading of new growth by taller standing residue (default = 50% reduction)
MODVEG_MIN_LIFESPAN_ADJUST_PORTION, % (D _{min,l})	50	maximum percentage of daily new growth lifespan despite shading of new growth by taller standing residue (default = 50% reduction)
<u>Monthly user inputs</u>		
VEG_PERENN_MONTHLY_PROD_PORTION, % (NPP _m)	8.33	12 monthly NPP percentages at maturity that sum to 100%
MODVEG_MONTHLY_SHOOT_LIFESPAN, d (l _s)	60	12 monthly average lifespan values for aboveground live biomass
MODVEG_MONTHLY_ACTIVE_TO_WOODY_PORTION, % (f)	30	12 monthly percentages representing the fraction of active roots transferred to the woody root pool at the end of their lifespan
MODVEG_MONTHLY_ROOT_SHOOT_RATIO (RS*)	2, 0.5	12 monthly estimates of RS*/target root/shoot ratio (default = 2.0 for perennial vegetation and default = 0.5 for annuals)
MODVEG_MONTHLY_DEATH_TO_EXTERNAL, %	0	12 monthly fractions of aboveground structure that does not become dead biomass on shoot death (lost to respiration)
<u>Seedling growth inputs</u>		
VEG_PERENN_NUM_YRS_TO_MATURITY, yr		years from establishment to maturity
VEG_PERENN_SEEDING_DATE, mon/day	1/0	normal seeding date (default = not specified, full-year calculations begin on 1 Jan.)
VEG_PERENN_OVERALL_GROWTH_PATTERN	MIDDLE	part of season with fastest growth during establishment (EARLY, MIDDLE, LATE)
MODVEG_START_LIVE_ABOVEGROUND_BIOMASS, kg ha ⁻¹	0	initial value of aboveground live biomass when seeded (0 = treat as mature)
MODVEG_START_STORAGE_BIOMASS, kg ha ⁻¹	0	initial value of storage biomass when seeded (0 = treat as mature)
MODVEG_START_ROOTMASS, kg ha ⁻¹	0	initial value of active root when seeded (0 = treat as mature)
MODVEG_START_OLD_ROOTMASS, kg ha ⁻¹	0	biomass of live woody roots when beginning growth in the presence of existing perennial vegetation
VEG_MODVEG_INITIAL_RAY_HT (h _L)	2	multiplier to allow taller growth of seedling vegetation [compared with mature height at the same biomass (=1 for no effect)]
VEG_MODVEG_INITIAL_RAY_BIOMASS_PORTION, %	50	percentage of maximum biomass when "leggy" seedling growth effect disappears completely

$$\frac{dB_{xs(i)}}{dt} = \lambda_s \frac{dB_{x(i)}}{dt} - D_{xs(i)} - H_{l(i)} \quad [19]$$

where $D_{s,x(i)}$ is the death of aboveground live biomass that is added to a standing dead residue pool on the i th day and $H_{l(i)}$ is the removal of live aboveground biomass by harvest operations. Similarly,

$$\frac{dB_{xr(i)}}{dt} = \frac{dB_{xs(i)}}{dt} \left(\frac{1}{\lambda_s} - 1 \right) - D_{xr(i)} \quad [20]$$

where $D_{r,x(i)}$ is the sum of the daily death of the active and woody root pools that are added to separate dead root residue pools. Finally,

$$B_{xs(i)} = B_{xs(i-1)} + \frac{dB_{xs(i)}}{dt} \quad [21]$$

$$B_{C(i)} = B_{C(i-1)} + \frac{dB_{C(i)}}{dt} \quad [22]$$

$$C_{(i)} = \frac{B_{C(i)}}{B_{xs(i)}} \quad [23]$$

The following sequence of steps is followed to develop appropriate a_i values for Eq. [16]. With the same standard procedures used to disaggregate monthly temperature and rainfall values into daily values (USDA-ARS, 2008), RUSLE2 disaggregates the products of the user-specified monthly production estimates and initial annual NPP target, NPP_T , into initial daily NPP values. Using daily disaggregated shoot lifespan values on the day of biomass production, RUSLE2 then calculates a target annual forage production value as the amount of biomass that grows above an arbitrary “assumed biomass at forage removal to get total production” each day summed across the year. RUSLE2 iteratively adjusts a common internal growth multiplier used to multiply the incoming values of $dB_{xs(i)}/dt$ in Eq. [21]. The model then works backward through Eq. [19], [17], and [20] and ultimately solves Eq. [16] for a_i . Through an iterative process, the internal growth multiplier is adjusted until the total annual “potential” forage production calculated as the annual sum of biomass harvested daily above the “potential cut height” is within 1% of the “annual potential forage harvest target.”

Once the model produces the correct potential forage production, it is assumed that the a_i values correctly represent the ideal unharvested vegetative growth. When a RUSLE2 user specifies as part of a management description a target crop yield different from that of the “potential” yield saved with the underlying vegetation description, RUSLE2 iteratively determines the value of NPP that achieves the user-entered average annual forage target. In this way, RUSLE2 users developing management descriptions can specify yield in terms of forage or grain harvested rather than NPP, and RUSLE2 automatically determines the appropriate daily a_i values. The resulting

vegetation description and the underlying model are then used by RUSLE2 to dynamically adjust canopy and residue production in response to alternative harvest scenarios.

If the vegetation being described is declared to be mature, RUSLE2 iterates through time until beginning values for root and shoot structure and carbohydrate substrate values are stable. If the user specifies initial values for shoot, root, or substrate carbohydrate values, then the calculations proceed from those initial values on a specified planting date and continue for the number of years to maturity specified by the user, after which growth transitions to a mature description.

In developing a forage description, the developer adjusts the total annual NPP target value, the maximum forage height, and the optimum potential cutting height until a desired “annual potential forage harvest target” is produced. For vegetation growing under conditions of plentiful water and nutrients, the “plateau aboveground biomass” is the aboveground biomass below the potential cutting height during the part of the year when potential biomass is harvested every day and should be close to 1500 kg ha^{-1} . This is the structural shoot biomass value determined using Eq. [15] with the default $K_B = 170 \text{ kg ha}^{-1}$ (Table 2) that yields a daily NPP value of 90% of the maximum production rate and is consistent with the optimal herbage level reported by Bransby et al. (1988).

Residue Tracking

The monthly description of NPP and effective lifespans of the live biomass permit RUSLE2 to model continual creation of above- and belowground plant residues. RUSLE2 tracks dead biomass in the following several layers (USDA-ARS, 2008): standing residue, surface residue (litter), and buried residue and dead roots in 24, 2.5-cm-thick soil layers. In the new model, when the aboveground live biomass reaches its lifespan, that biomass is transferred into the standing dead residue pool, controlled as described below. Standing residue decays at a rate equal to a user-specified fraction of that of surface residue or subsurface residues, which are assumed to decay at the same rate. Standing residue is gradually converted to surface residue as a function of the loss of mass of stem bases, which are assumed to decay at the same rate as surface residues (USDA-ARS, 2008).

Vegetation descriptions created with the model described here may also contribute to three additional residue pools: surface residue, active root residue, and woody root residue. Each residue pool has an associated base decomposition constant, φ , that reflects material properties such as particle size and composition. The actual decomposition of each pool is linked to climate and may be reduced by either cold or dry weather (USDA-ARS, 2008). Residue created or added to each pool at a specific time decays as a unique batch.

Plant Growth Model Refinements

After the core of the new plant growth representation was incorporated into RUSLE2, the new functionality was submitted to substantial testing by working groups composed of NRCS state and regional agronomists and grazing lands specialists. Based on feedback and requests, it became clear that refinements were needed to allow users to describe the systems

of interest. Through an iterative process of modification and testing, the following refinements were added.

Location Effects

In initial trials of the plant growth model, it was apparent that for cold locations the algorithm carried too much of the NPP into the winter months. It was therefore decided to add an additional restriction on the a_i values based on the insolation for the location but to give the developer of the vegetation description some control over the sensitivity of growth to that restriction. Using the approach recommended by the National Aeronautics and Space Administration (2011) and assuming solar noon and none of the additional complications of orbit eccentricity and other factors, an insolation factor I_i for each day was calculated based on the latitude defined in the location–climate description, with a default latitude of 35° N if none is specified. The I_i values are not insolation amounts but rather relative values scaled to give a maximum of 1.0 on the day of greatest actual insolation.

In calculating the a_i values as described above, the resulting value is checked against a limit defined as

$$a_{i,\text{limit}} = PI_i \left\{ D_{\text{max}} \left[\left(\frac{D_i}{D_{\text{max}}} \right)^{s/(s+1)} \right] \right\} \quad [24]$$

where P is a dimensionless user-set “production multiplier” ranging in value from 1 to 6 that limits extremes of the resulting a_i values, I_i is the relative insolation value for this day as described above, D_i is the $dB_{x,s(i)}/dt$ value for this day, D_{max} is the largest $dB_{x,s(i)}/dt$ value during the year, and s is a dimensionless user-defined sensitivity value ranging from 0 to 20. If the calculated value of a_i for this day is greater than $a_{i,\text{limit}}$, a_i is set equal to $a_{i,\text{limit}}$ and the other related values are adjusted accordingly. The P parameter controls whether the limit is likely to come into play at all, with a low value (near 1) indicating a strong likelihood that the growth will be insolation limited. The impact of the sensitivity parameter s can be examined by exploring the extremes. For $s = 0$, $a_{i,\text{limit}} = PI_i D_{\text{max}}$, so the limit tracks the insolation curve and is insensitive to the value of D_i . For $s = 20$, $a_{i,\text{limit}} \sim PI_i D_i$, so the limit will track the product $I_i D_i$, whose values may either reinforce or cancel each other.

Lifespan Spread

It was stated above that the aboveground structure is assumed to have an effective lifespan that the user can set to different values for each month. When the vegetation structure “born” on a particular day reaches the lifespan for that day, the live biomass is converted to the standing residue pool. In reality, any single lifespan value is a compromise between the lifespans of various plant parts. Leaves may have a shorter lifespan than culms, but the shoot lifespan is an average. Also, when mixtures of vegetation are described, the lifespan must reflect that mixture. To account for variation among vegetation parts and to avoid abrupt changes in residue creation rates, the lifespan for a day is treated not as a single value but rather as a distribution whose central value is the declared lifespan. The assumed distribution is triangular, with a base width defined by the “shoot lifespan spread portion,” which defaults to 40%

of the lifespan value. Thus, for vegetation with a 60-d lifespan, some shoot biomass will die after 48 d and some will live until 72 d, with peak death occurring on the 60th day. As implemented, the lifespan spread applies only to aboveground live biomass and not to root biomass pools.

Substrate Carbohydrate Distribution in Canopy

As part of a vegetation description, the user indicates the location of substrate carbohydrate as a percentage of the current vegetation maximum canopy height. If the user declares this parameter to be zero, no substrate carbohydrate is removed when shoots are harvested, whereas if this parameter is set equal to 100% (the default value), carbohydrate is removed in equal proportion to the fraction of shoot structure removed. In all cases, carbohydrate is assumed to be uniformly distributed throughout the canopy below a height equal to the specified fraction of the maximum canopy height. Removing substrate carbohydrate retards the regrowth of vegetation until the substrate pool is restored, but in the current scheme this takes only a few days.

Vegetation Height–Biomass Relationships

RUSLE2 assumes a linear relationship between canopy height and aboveground live biomass, but the slope of the relationship can change each day in response to management (Fig. 1). Internally, RUSLE2 tracks the height biomass relationship in terms of “rays” defined by the normalized variables $b = \text{height}/H_{\text{max}}$ and $b = \text{biomass}/B_{\text{max}}$, where H_{max} is the

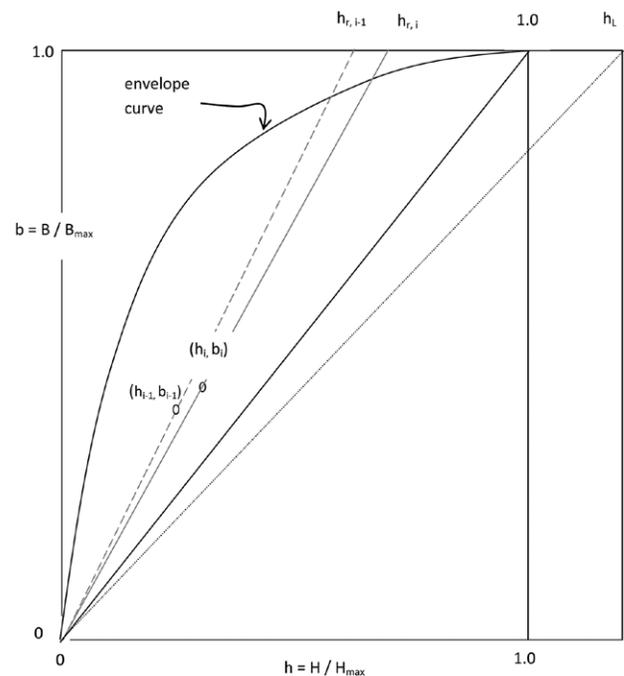


Fig. 1. Illustration of adjustments to linear biomass–height relationship in RUSLE2. Biomass is expressed as a dimensionless ratio, b , of current biomass to maximum biomass and height is expressed as a dimensionless ratio, h , of current height to maximum height. New biomass b_i has an associated height h_i falling on the “ray” passing through the origin and the current target ray height, $h_{r,i}$. The ray through h_L is used to define initial “leggy” growth of seedlings, which is reset to $h_{r,i=1}$ on cutting or tends toward that slowly with extended growth.

maximum uncut biomass height specified by the user and B_{\max} is the maximum daily aboveground live biomass determined by the model in the absence of any harvest. For any day, the current target biomass “ray” goes through the origin and the point $(b_{r,t}, 1)$, and new biomass produced on that day is assumed to have a biomass–height relationship defined by that target ray. The ray for mature uncut vegetation or for vegetation with no sod-forming behavior goes through (1,1), so $b_{r,t} = 1$. For sod-forming vegetation that has recently been repeatedly cut, $b_{r,t} < 1$, while for “leggy” seedling growth, $b_{r,t} > 1$.

A parameter called the envelope midpoint portion, b_m , controls whether the slope of the height–biomass line is affected by defoliation operations. If this parameter is set to 0.5 (default), there is no sod-forming tendency, so cutting the vegetation at half its current height removes 50% of the biomass and has no influence on the slope of the height–biomass line for subsequent growth. In contrast, if this parameter is something less than 0.5, then on cutting at half the current canopy height, 50% of the biomass is removed but $b_{r,t}$ will be reduced when new growth occurs, thus altering the slope of the height–biomass line for future growth. The degree of sod effect is defined by the “envelope curve” shown in Fig. 1, which is of the form $b_i = (b_p)^c$. The value of c is based on b_m , the normalized height at which $b_i = 0.5$, so $c = \ln(0.5)/\ln(b_m)$. A value of $b_m = 0.5$ means there is no sod-forming effect, so the height–biomass point is restrained to sliding up and down the diagonal vegetation ray through $b_r = 1.0$. A lower b_m value means a greater sod-forming effect.

Each daily biomass addition is tracked individually, allowing it to die at the end of its lifespan. The target ray height $b_{r,i}$ associated with that day is also stored. The amount of biomass below a specified height H (e.g., for a hay cutting at height H) is then $B = B_{\max}(H/H_{\max})S$, where $S = [\sum(B_i/b_{r,i})]/B_t$, B_i is the daily biomass addition for the i th day, $b_{r,i}$ is the stored target ray height for that day, and $B_t = \sum B_i$ is the current total live aboveground biomass. Similarly, the height H at which we would need to cut the vegetation to be left with a specified biomass B is $H = H_{\max}(B/B_{\max})/S$.

The rate at which the height–biomass relationship is altered in response to repeated defoliations—or reverts to the base height–biomass relationship in the absence of defoliation—is controlled by two parameters. The first is the “days for full height adjustment” parameter, D_m , which determines how many days vegetation must grow without cutting for the total sod effect to disappear. The nominal distance that the ray height b_r moves each day is

$$\Delta b_r = \frac{I - (H_p/H_{\max})}{D_m} \quad [25]$$

If there is cutting or removal on this day, then $b_{r,i} = b_{r,i-1} - \Delta b_r$. If there is no cutting or removal, then the second parameter “maximum cut interval to keep from getting more leggy,” D_L (d), becomes significant. If the number of days since the most recent cutting is $-D_L/2.0$, the target ray height continues to move downward as $b_{r,i} = b_{r,i-1} - \Delta b_r$. Once past this point, the target ray height moves upward as $b_{r,i} = b_{r,i-1} + \Delta b_r(a_i/a_{i,\max})$, where the last term limits the changes in plant growth characteristic to the periods of active growth, thus limiting the loss of a sod-forming tendency during dormancy. There are

additional limits on the movement of the target ray height $b_{r,i}$. Excluding the special “leggy seedling growth” described below, $b_{r,\min} = H_p/H_{\max}$, while $b_{r,\max} = 1.0$. Also, if any b_i value as defined by the biomass b_i and the current $b_{r,i}$ falls to the left of the envelope curve, the value of $b_{r,i}$ is increased to put the b_i value on the curve.

In comparison to mature vegetation, seedlings often achieve a specified height with lower total aboveground biomass. This “leggy” behavior is simulated by a user-defined seedling $b_r > 1.0$, displayed in Fig. 1 as b_L . In addition, the user sets the value of “birth portion of maximum for end of seedling growth” (P_b), defining the total birth that must occur before the current ray height has moved back to $b_r = 1.0$. If the birth this day is b_p , then the movement of the current ray height during this “leggy growth” period is

$$\Delta b_r = b_i \frac{b_i - 1}{P_b B_{\max}} \quad [26]$$

and the next day’s target ray height is $b_{r,i} = b_{r,i-1} - \Delta b_r$. If a cutting or grazing operation occurs on this day, the program immediately resets $b_{r,t} = 1.0$, ending the “leggy” behavior.

Shading Effects

To reflect the negative impact on growth of extensive standing residue shading the live biomass when it is small, RUSLE2 can reduce the primary productivity and the lifespan of the vegetation produced each day. The adjustment to each variable is calculated independently based on the height of the live biomass, the height of standing residue, and the ratio R_c of the mass of standing residue to the total aboveground biomass:

$$R_c = \frac{M_r}{M_l + M_r} \quad [27]$$

where M_r is the standing residue mass and M_l is the aboveground live mass. The user also specifies minimum values for the fractional adjustments to production, $D_{\min,p}$, or lifespan, $D_{\min,l}$. The default value for these is 50%, which means birth and lifespan can each be cut in half by shading. The actual adjustments are calculated as

$$D_j = D_{cj} + (1 - D_{cj}) \frac{H_l}{H_r} \quad [28]$$

$$D_{cj} = 1 - (1 - D_{\min,j})(R_c) \quad [29]$$

where H_l is the height of the live aboveground biomass, H_r is the height of standing residue, and D_j is a multiplicative factor that reduces $a_{(j)}$ in Eq. [16] if subscript $j = p$ and reduces l_s in Eq. [10] if subscript $j = l$.

APPLICATIONS

To demonstrate the flexibility of the new RUSLE2 plant growth model, three case studies derived from published literature and representing a diverse mixture of climates and plant types are described below.

Konza Prairie

Research at the Konza Prairie near Manhattan, KS, has provided insight into the behavior of tallgrass prairies with and without such management inputs as burning, grazing, and fertilization during a number of wet and dry years (Knapp et al., 1985, 1998; Abrams et al., 1986; Hayes and Seastedt, 1987; Seastedt, 1988; Briggs and Knapp, 1991; Rice et al., 1998). In these studies, the assumption was often made that when biomass sampling was done at the time of peak standing biomass (August), current year losses to senescence, leaf shedding, insect feeding, and decay were negligible (Knapp et al., 1998). These studies confirmed that in unburned, ungrazed tallgrass prairie, standing dead biomass exceeds peak live biomass in most years (Abrams et al., 1986) and most dead biomass (foliage and flowering stem detritus) decomposes as standing dead material without ever becoming surface litter (Seastedt, 1988). In the unburned, ungrazed condition, *litterfall* “consists of insect frass, flower parts, forb leaves, and small fragments of grass foliage and flowering stems that are physically capable of dropping through the often matted standing dead vegetation,” and contributes $1.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ to the surface (Seastedt, 1988). When measured at the time of peak live biomass, current-year standing dead material was 0.75 Mg ha^{-1} in unburned prairie (Briggs and Knapp, 1991), equal to 33% of live biomass but representing <15% of the total dead material (Abrams et al., 1986). Biomass production was higher following burning in years with normal precipitation, but burning decreased biomass production during drought years so that the 12-yr average annual biomass production was not affected by burning (Knapp et al., 1998). Rice et al. (1998) reported that the mean belowground biomass (including rhizomes) was 3.2 times the peak aboveground biomass, averaging 19.1 Mg ha^{-1} below ground (including 4.9 Mg ha^{-1} rhizomes) and 6.3 Mg ha^{-1} above ground.

To simulate this system in RUSLE2, the default parameters describing how standing residues decompose and are converted to surface residues were modified. To simulate the persistence of standing residue, the rate at which stem bases decay relative to surface residue was decreased to 0.2 from the default of 1.0 and the rate at which standing residues decay relative to surface residue was increased to 0.5 from the default of 0.3. These changes allowed RUSLE2 to capture the situation where dead stems do not fall over because they are held up by other living and recently dead culms, yet they continue to decay at their bases at a rate greater than the average for standing dead residues. Tall standing residues reduce growth rates and increase tissue turnover due to shading. To simulate this, maximum reductions to daily primary productivity and shoot lifespan were both set to 50%.

With primary productivity set at $5.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, shoot lifespan at 70 d, maximum canopy height at 80 cm, potential cut height at 35 cm, and the target root/shoot ratio set to 6.0 (Table 3) and all other parameters left at their default values (Table 2), monthly primary production percentages were selected to create a growth curve for a mature perennial vegetation that approximated the ungrazed prairie growth observed following burning in 1983 (Knapp et al., 1985). Predicted live and dead biomass amounts were then compared with

Table 3. RUSLE2 parameters (monthly net primary productivity, NPP_m ; shoot lifespan, I_s ; the fraction of active roots that become woody roots, f ; and the ratio of full-depth live roots to total live aboveground biomass, RS^*) used to describe the three vegetation applications.

Month	NPP_m Mg ha^{-1}	I_s d	f	RS^*
<u>Konza Prairie, Kansas†</u>				
Jan.	0	70	30	6
Feb.	0	70	30	6
Mar.	0	70	30	6
Apr.	5	70	30	6
May	25	70	30	6
June	31	70	30	6
July	23	70	30	6
Aug.	9	70	30	6
Sept.	6	70	30	6
Oct.	1	70	30	6
Nov.	0	70	30	6
Dec.	0	70	30	6
<u>Ryegrass, UK‡</u>				
Jan.	2	60	30	2
Feb.	2	60	30	2
Mar.	8	60	30	2
Apr.	16	60	30	2
May	17	60	30	2
June	16	60	30	2
July	13	60	30	2
Aug.	11	60	30	2
Sept.	6	60	30	2
Oct.	4	60	30	2
Nov.	3	60	30	2
Dec.	2	60	30	2
<u>Switchgrass, Tennessee§</u>				
Jan.	0	50	50	4
Feb.	0	50	50	4
Mar.	1	50	50	4
Apr.	6	50	50	4
May	12	50	50	4
June	18	50	50	4
July	18	50	50	4
Aug.	18	50	50	4
Sept.	17	50	50	4
Oct.	9	50	50	4
Nov.	1	50	50	4
Dec.	0	50	50	4

† Target annual net primary productivity (NPP_T) = $5.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$; maximum canopy height achieved at maturity (H_{max}) = 80 cm; potential cut height (H_p) = 35 cm; envelope midpoint portion (h_m) = 0.5; base decomposition constant (φ) = 0.008 d^{-1} .

‡ NPP_T = 11.8 or 16 $\text{Mg ha}^{-1} \text{ yr}^{-1}$; H_{max} = 40 cm; H_p = 5 cm; h_m = 0.35; φ = 0.017 d^{-1} .

§ NPP_T = 21 $\text{Mg ha}^{-1} \text{ yr}^{-1}$; H_{max} = 120 cm; H_p = 25 cm; h_m = 0.5; φ = 0.008 d^{-1} .

observations on areas without late winter burning (Fig. 2). The results illustrate how a RUSLE2 vegetation description created to match the potential growth of a particular environment and management can dynamically adjust to alternative management scenarios, reasonably approximating the amounts and timing of canopy and residue production that influence soil erosion processes.

Sod-Forming Ryegrass

Two studies were used as the basis for creating a vegetation description of perennial ryegrass (*Lolium perenne* L.) grown in the UK. One involved alternative grazing heights in Hillsborough, Northern Ireland (Chestnutt, 1992; Binnie and Chestnutt, 1994), while the other involved the effect of grazing vs. silage harvest on subsequent stand morphology in Aberdeen, Scotland (Hepp et al., 1996). A single vegetation description was developed to approximate the response of ryegrass to these management scenarios (Table 3). The only difference between the descriptions for these applications was that the target net primary productivity was set at 11.8 Mg ha⁻¹ for Hillsborough and at 16 Mg ha⁻¹ for Aberdeen to match the published total yields.

Binnie and Chestnutt (1994) studied perennial ryegrass pastures continuously grazed by sheep, with stocking rates adjusted weekly to maintain sward heights of 3, 5, 7, or 9 cm. Leaf, stem, dead, and total aboveground biomass were measured every 2 wk during the two grazing seasons. The first grazing season was from March to mid-July (Period 1), at which time all pastures were clipped to a height of 5 cm. The second grazing season was from after clipping until the end of the grazing period between 5 and 23 October (Period 2). The results of 3 yr were averaged for each of the two seasons and indicated that total aboveground biomass increased with grazing height but biomass density (biomass per unit canopy height) decreased with increasing canopy height. Using an envelope midpoint portion $h_m = 0.35$ allowed the RUSLE2 routines to approximate this behavior (Fig. 3).

Hepp et al. (1996) evaluated the canopy density and productivity of perennial ryegrass continuously grazed from 10 Aug. to 19 Nov. 1987 after receiving different pretreatments. One area had been continuously grazed from early May until early August, with stocking rates adjusted to maintain a sward height of 4 to 5 cm. The other area was closed to grazing in early May and was cut for silage on 26 June and 28 July at a height of 6 cm. Stocking rates were adjusted to maintain sward heights of 4 or 8 cm on subsections of each pretreated area. Results indicated that during the sampling period between 17 August and 9 October there was greater tiller density, more growth, more senescence, more net growth, and more standing biomass for both sward heights following a grazing history rather than a haying history. As expected, growth, senescence, and net and standing biomass were higher with an 8-cm sward height than with a 4-cm sward height. The RUSLE2 vegetation description using default values of $D_L = 7$ d and $D_m = 90$ d mimicked this behavior (Fig. 4).

Bioenergy Switchgrass

Garten et al. (2010) studied 4-yr-old switchgrass (*Panicum virgatum* L.) grown on a silt loam soil in western Tennessee (35.6° N). Field trials involving four cultivars were planted during the spring of 2004 and were harvested annually in October or November in 2004, 2005, and 2006. During 2007, above- and belowground biomass was sampled in the spring (2–4 April), summer (23–25 July), and fall (29–31 October). Surface litter was sampled separately from the aboveground biomass, and roots were separated into living and dead root pools. A RUSLE2 vegetation description was developed that mimicked the observed behavior (Fig. 5). To match the observed

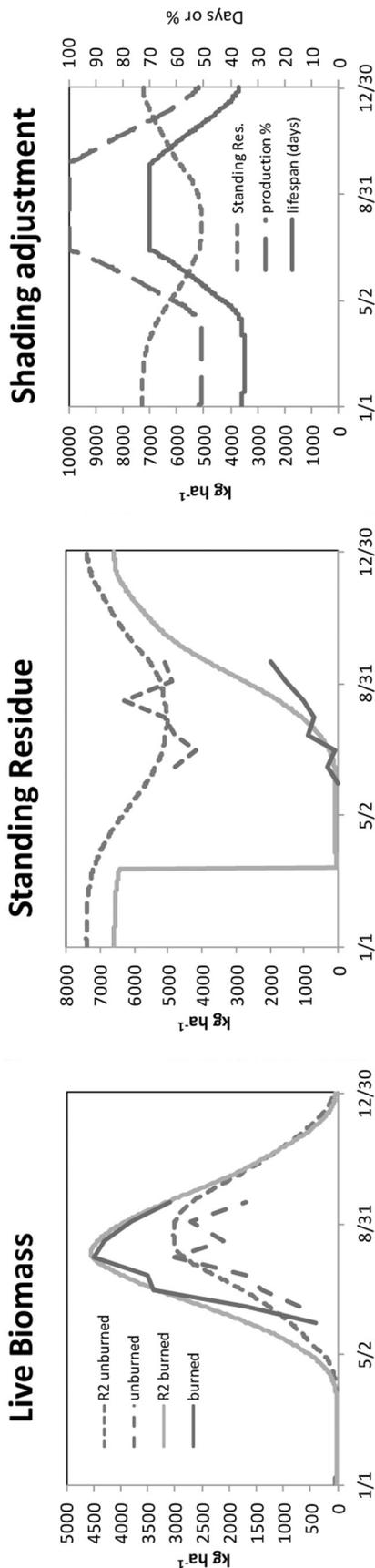


Fig. 2. Live aboveground biomass and standing dead biomass for burned and unburned areas of the Konza Prairie in 1983 (Knapp et al., 1985) and RUSLE2 simulations (R2). Maximum shading effects for both primary productivity and lifespan were set at 50%; without burning to remove standing residue, shading reduced and delayed growth. Even with burning, which maximized shoot lifespan, significant standing dead residue developed by the time of peak live biomass.

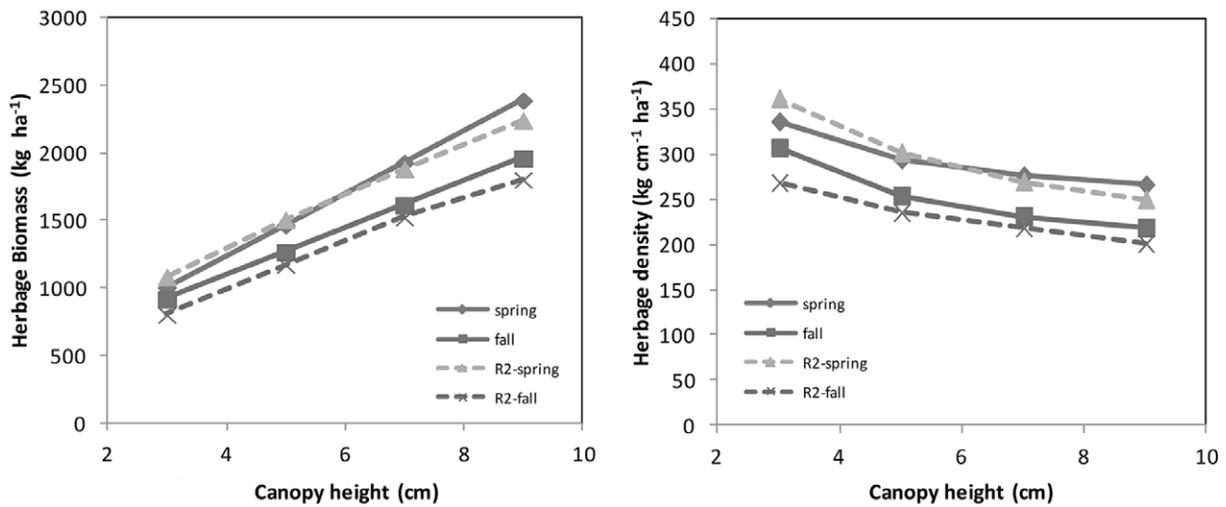


Fig. 3. Observed and modeled by RUSLE2 (R2) total aboveground biomass and herbage density of ryegrass pasture continuously grazed by sheep to maintain four canopy heights (Binnie and Chestnutt, 1994). Increased herbage density with decreasing canopy height with repeated defoliation is referred to in RUSLE2 as a “sod-forming tendency.”

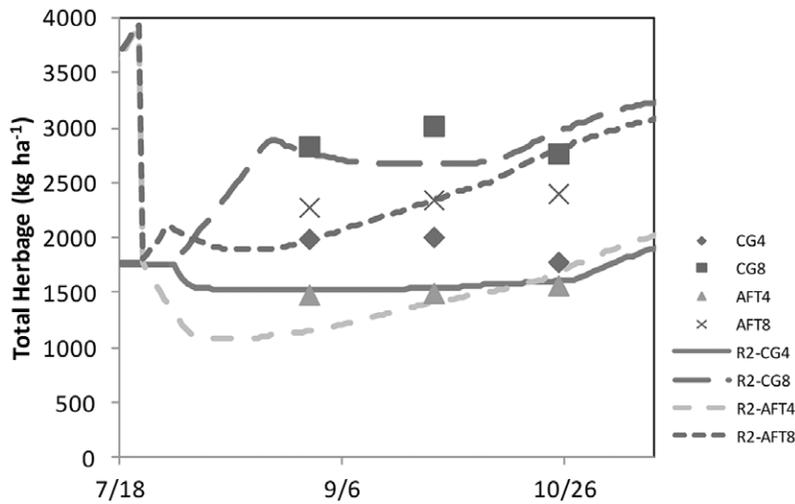


Fig. 4. Observed and modeled by RUSLE2 (R2) total aboveground biomass continuously grazed by sheep to maintain canopy heights of 4 or 8 cm after pretreatment from early May to early August of either continuous grazing (CG) at a canopy height of 5 cm or harvesting for silage at a height of 6 cm (AFT) on 26 June and 24 July (Hepp et al., 1996). This illustrates that increased herbage density that developed during CG persisted for >60 d.

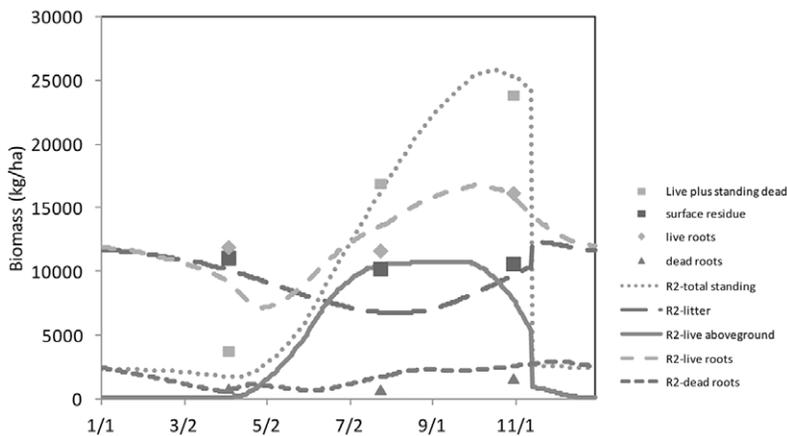


Fig. 5. Observed and modeled by RUSLE2 (R2) total aboveground biomass, surface residue, and live and dead roots of switchgrass managed as a bioenergy crop near Jackson, TN (Garten et al. 2010).

quantities of living and dead roots, the target root/shoot ratio was increased to 4.0 and the percentage of active roots becoming woody was increased from the default 30 to 50% (Table 3).

DISCUSSION

The primary purpose of RUSLE2 is to predict the average annual sheet and rill erosion and sediment delivery from hillslopes for conservation planning. RUSLE2 was calibrated based on analysis of a large body of erosion plot data and predicts the timing of erosion through each year of a rotation but does not vary erosion due to year-to-year weather variability. Subfactor analysis of conditions including residue and canopy cover, surface roughness, and soil biomass was used to extend the erosion predictions to conditions not well represented in the original data. For this approach to be successfully extended to perennial vegetation systems, the amount and timing of plant residue and biomass creation must be reasonably approximated, which was very difficult using the previous approach.

Model Flexibility

The three examples above demonstrate that the new RUSLE2 algorithms have the flexibility to approximate the creation of standing, surface, and subsurface residues in a wide range of herbaceous perennial systems using information that is generally known to producers or conservationists, such as the target yield and the growth pattern through the year. Each of the case studies highlights a different aspect of the new RUSLE2 herbaceous plant growth model. The Konza Prairie example illustrates how shading adjustments to the birth rate and shoot lifespan reduce and delay primary productivity when residues are not removed (burned). The ryegrass example illustrates how the

vegetal density of sod-forming grasses increases in response to repeated close grazing or mowing and how that increased density is lost with time when frequent harvests are stopped. The switchgrass example illustrates how having default root residue decomposition parameters different from shoot residue parameters resulted in a reasonable match to observed shoot, live root, and dead root biomass pools. In previous RUSLE2 vegetation descriptions, dead roots were assumed to have the same decay characteristics as shoot residues. Both the Konza Prairie and switchgrass examples illustrate that the default root/shoot target may need to be increased from the default 2.0 for warm-season grasses, particularly for descriptions appropriate to semiarid climates (Hanson et al., 1988; Schuman et al., 1999; Corson et al., 2006).

Comparison with Other Models

Many herbaceous plant growth models have been developed and incorporated into modeling systems that serve a variety of purposes. The complexity and level of detail represented in these models vary widely, from hourly leaf-level photosynthesis of sunlit and shaded leaf area in CROPGRO (Pedreira et al., 2011), to multiple-species community-level representations using a daily time step and considering competition for water, nutrients, and light in SPUR (Hanson et al., 1988), ALMANAC (Kiniry et al., 1992), GRASIM (Zhai et al., 2004), and the SGS pasture model (Johnson et al., 2003). All of these models are dynamically linked to daily weather data and estimate growth through estimates of leaf area index, light interception, and radiation use efficiency. In contrast, the RUSLE2 routines focus on the creation and tracking of live and residue biomass that are needed for erosion prediction purposes. It is an engineering tool in the sense described by Passioura (1996).

It may be useful to compare the behavior and complexity of the new RUSLE2 routines to the popular EPIC plant growth model (Williams et al., 1989), which has been widely implemented and adapted as a component of several natural resources modeling systems including WEPP, WEPS, and APEX. In the EPIC crop model, growth rates are based on daily solar radiation and intercepted light as restricted by above- and below-ground stress factors including water, nutrient, temperature, aeration, acidity, and compaction. Leaf area development and senescence are related to accumulated heat units. Harvest of a forage crop rolls back the accumulated heat units, thereby delaying senescence. The development of crop residue is not equally well developed in EPIC. Once a plant is mature, EPIC does not create residue or decay it until an operation converts standing dead plant material into surface residues.

In the new RUSLE2 model, plant growth is not directly linked to climate. Rather, the amount and pattern of primary productivity under optimal harvest management is specified by the user through commonly understood quantities that reflect the combination of all factors controlling growth, including available light, temperature, day length, fertilization, water balance, and species mixture. Through its underlying model, residue creation occurs continuously with a daily time step and residue estimates dynamically respond to alternative harvest scenarios that alter birth, death, root partitioning, sod formation, and shading effects.

The underlying conceptual model and equation structure in the new RUSLE2 routines represent greatly simplified versions of more detailed pasture models that evolved from concepts and approaches developed at the Grassland Research Institute, Hurley, UK (Johnson et al., 1983; Parsons et al., 1983). With time, these concepts were elaborated into a number of models that considered the effects of intermittent defoliation (Parsons et al., 1988) and supported species mixtures (Thornley et al., 1995). The GRAZingSimulation Model (GRASIM) (Mohtar et al., 1997; Zhai et al., 2004) in the United States and the Sustainable Grazing Systems (SGS) pasture model (Johnson et al., 2003) in Australia are members of this family. In the RUSLE2 implementation, linkages to light, water, and nutrient limitations were removed and replaced with user knowledge of the expected seasonal growth patterns and yield levels.

The new RUSLE2 procedures improve the estimates of residue creation compared with earlier versions, while reducing the number of vegetation descriptions needed to characterize a farming system. Older RUSLE2 procedures never created standing dead residues unless the vegetation was declared killed by an operation and only created surface residues during periods when the vegetation canopy declined. In contrast, the new procedures more realistically produce continuous additions of standing, surface, and subsurface residues. In most cases, the resulting changes reduce the estimates of soil erosion from perennial systems relative to the older procedures. Furthermore, the new procedures are easier to implement than the older RUSLE2 procedures because the user no longer needs to develop separate vegetation descriptions to represent the expected growth between each harvest period. The new procedures require the creation of only a single vegetation description that dynamically responds to alternative management operations through the underlying model.

Limitations and Extensions

The current approach makes many simplifications and has certain limitations. First, like vegetation descriptions currently used by the NRCS, the new implementation supports the growth of only a single species at a time. If a mixture of plants is to be simulated, a hybrid vegetation description must be created by the user to reflect the overall annual growth pattern of the mixture. Similarly, residues created by the vegetation mix must be characterized with a single decomposition coefficient that does not change as decomposition progresses. The second limitation is that a single, possibly hybrid, vegetation description must also be characterized with a single set of shoot lifespans. Even though leaflets may have shorter lifespans than stems (Fuess and Tesar, 1968), an effective average must be specified. The concept of shoot and root lifespans can be compared with a fractional senescence rate. A lifespan of 50 d may imply a senescence rate of 0.02 d^{-1} . By having an age associated with the biomass born on each day, however, no senescence occurs during the first 40 d of growth if the “shoot lifespan spread portion” = 40%, so the current model alters the timing of residue creation compared with a senescence coefficient such as that used in CROPGRO (Pedreira et al., 2011). Third, the current model is applicable only to the description of herbaceous vegetation because it does not include a protected pool within which woody biomass can accumulate. Woody

biomass is an important component of forest and rangeland brush systems. Finally, separate vegetation descriptions must be developed to reflect management alternatives that affect the timing of the primary production of optimally harvested swards, such as single vs. multiple fertilizer applications or irrigated vs. dryland production. While the model does increase senescence (decrease lifespan) and reduce birth in response to residue shading, it does not increase the senescence rate in response to environmental stress as SPUR does (Corson et al., 2006). Nevertheless, despite these simplifications, RUSLE2's new vegetation and residue tracking capture the main effects that allow the creation of residues throughout the year in perennial systems and reasonably reflect how residue creation will be affected by biomass harvest.

Soil erosion and forage productivity are influenced by both spatial and temporal variability in precipitation, but RUSLE2 seeks to predict long-term seasonal patterns and average annual erosion rates. Although statistical procedures to assess the impact of runoff events with a specified return period are supported (Dabney et al., 2011), year-to-year variability is not considered. Similarly, the perennial forage descriptions in RUSLE2 ignore year-to-year variability in climate. Vegetation descriptions represent long-term average biomass and residue production amounts that affect the susceptibility of the system described to soil erosion. It is recognized and understood that managers must adapt to short-term variability in rainfall patterns by adjusting management to seize opportunities and evade hazards that will actually vary significantly from place to place and year to year within the represented region (Díaz-Solis et al., 2003), but the management practices described in RUSLE2 and the vegetation responses to these practices should reflect the long-term averages of a stable state. Database development for semiarid regions may be facilitated by using an approach similar to that described by Díaz-Solis et al. (2003) as part of the Simple Ecological Sustainability Simulator (SESS), in which annual primary productivity was estimated based on annual rainfall, soil characteristics, and range condition, and monthly growth proportions were estimated using monthly temperature and rainfall.

CONCLUSIONS

Earlier versions of RUSLE2 underestimated residue cover because the assumption that surface residues were created only during periods of canopy decline was invalid for perennial systems, which led to overprediction of sheet and rill erosion from grazing and hay lands. The new procedures produce more realistic amounts of residues and furthermore make it much easier to describe RUSLE2 vegetation. Whereas in earlier versions of RUSLE2 separate vegetation descriptions had to be created for multiple growth periods following each harvest, in the new procedures a single vegetation description is grown for periods up to several years and the underlying model adjusts growth and residue creation in response to harvest operations. Vegetation is described in terms of parameters that are generally known by farmers and conservationists, including expected yield level, monthly portions of growth, mature canopy height, and optimum cutting height. Other parameters are assigned default values (Table 2) that do not need to be changed but that the user can modify if desired based on local knowledge. For

example, the target root/shoot ratio is given a default value of 0.5 for annual forages and 2.0 for perennial vegetation. Higher values may be appropriate for warm-season grasses and semi-arid environments, but erosion estimates based on the default values will be reasonable.

A single vegetation description is created to describe species mixtures, a single shoot lifespan must apply to all aboveground plant parts, and the crop residues created at different times during the year are characterized with a single decay constant. Obviously, a more elaborate set of descriptions could be created with multiple species with multiple residue types that might vary in quality (decomposition rate) during the year. Trying to model the interactions between the species would entail its own risks and uncertainties, however, and would add complexity well beyond the need of a model for predicting management effects on soil erosion. The purpose of RUSLE2 is to predict erosion for conservation planning, and the new perennial vegetation technology improves this function. Currently, the NRCS is finalizing vegetation and harvest management descriptions for "forage management zones" that cover the eastern half of the United States. A subsequent study will describe the new interface tools and planting and harvest processes in RUSLE2 that simplify the creation of management scenarios that take advantage of the new vegetation model. When modifications to the official NRCS database are completed, the new RUSLE2 capabilities will become available for use in NRCS field offices and for other users, enabling improved erosion estimates for grazing and hay lands as part of official conservation plans.

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