Fate of Spilt Sugars from Cane Harvest: Investigation and Modelling of the Phenomena


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1. INTRODUCTION

This report describes the investigations of the fate of sugars lost to the soil during harvesting of sugar cane. It includes results from field and laboratory experiments and the development of a model (BODOS). This report does not duplicate details of other work already published, but uses the model as the template to present the supporting evidence for the functions, rate constants and variables used in the model.

The Australian sugar industry is located along the coast of Queensland and Northern New South Wales. This places it in an environment where its impacts are closely scrutinised due to the population density being highest in the coastal plain. Fish kills have occurred in waterways located in cane growing areas and have been linked to depleted dissolved oxygen (DO). An understanding of the processes involved in the generation of runoff water with high biological oxygen demand (BOD$_5$) from cane paddocks was the subject of a project within the CRC for Sustainable Sugar Production. The results from this work culminated in the production of a model (BODOS) which predicts the BOD$_5$ of runoff water using a procedure that is outlined in this report.

2. MODEL STRUCTURE

The Model consists of the following structural elements:

- main model
- water balance sub-model
- parameter table
- climate input table
- output graphs and tables.

This report is designed to give the reader some idea of how to use the BODOS. The model is written using Modelmaker 3 and can be obtained from the senior author.

The water balance is the driver of the system, so we will start with the description of that submodel.

2.1 Water Balance Sub-Model

2.1.1 Compartments

The water balance model is based on that of Deardorff (1978) and uses a force/restore method to better determine soil evaporative losses. This model consists of two compartments, a surface and a bulk compartment (Fig. 1). The surface compartment is nested inside and is part of the bulk compartment. There is a transfer of water to or from the surface compartment from or to the bulk by an exchange coefficient. In Deardorff’s model this exchange coefficient ($C_1$) is an empirical parameter. Here it will be defined based on the soil water diffusivity and is approximated by:

$$C_1 = D \cdot \frac{2(\epsilon_b - \epsilon_a)}{(z_b - z_a)} - k \tag{1}$$

where $\epsilon_a$ is the volumetric water content of the surface layer [L$^3$ L$^{-3}$] and $\epsilon_b$ is the volumetric water content of the bulk layer [L$^3$ L$^{-3}$], $z_b$ is the depth of the bulk soil...
layer \([L]\), \(z_a\) is the depth of the surface soil layer \([L]\), \(k\) is the hydraulic conductivity \([L \, T^{-1}]\) and \(D^*\) is the constant soil water diffusivity \([L^2 \, T^{-1}]\) (Philip, 1969). The value of \(D^*\) can be approximated for a linear soil by (Philip, 1969):

\[
D^* = \frac{\pi S^2}{4. \mathcal{D}}
\]

where \(S\) is the sorptivity \([M \, T^{1/2}]\) (Philip, 1957), \(\mathcal{D}\) is the difference in the volumetric water content \([L^3 \, L^{-3}]\), \(\mathcal{D}_f\) is the final and \(\mathcal{D}_i\) is the initial water content. The use of a constant diffusivity when the soil is wet was found to be valid by Clothier and White (1981). It can also be shown for a linear soil that (Philip, 1969, eqn (127)):

\[
\frac{d k}{d \mathcal{D}} = \text{const} = k^*
\]

From eqn (3), assuming that at field capacity \((\mathcal{D}_{FC})\) that \(k(\mathcal{D}_{FC}) = 0\) the value of \(k^*\) is given by:

\[
k^* = K_s / (\mathcal{D}_s - \mathcal{D}_{FC})
\]

where \(K_s\) is the saturated hydraulic conductivity \([L \, T^{-1}]\) and \(\mathcal{D}_s\) is the saturated water content \([L^3 \, L^{-3}]\). The value of \(k\) is then calculated using:

\[
k(\mathcal{D}) = K_s \frac{(\mathcal{D} - \mathcal{D}_{FC})}{(\mathcal{D}_s - \mathcal{D}_{FC})}, \quad \mathcal{D} > \mathcal{D}_{FC}
\]

\[
to\mathcal{D} = \mathcal{D}_{FC}
\]

The flux between the compartments \((\text{FluxToSur})\) is calculated by substituting eqn (5) in eqn (1) to give:

\[
\text{FluxToSur} = D^* \frac{2(\mathcal{D}_b - \mathcal{D}_a)}{(z_b - z_a)} - K_s \frac{(\mathcal{D} - \mathcal{D}_{FC})}{(\mathcal{D}_s - \mathcal{D}_{FC})}
\]
Figure 1. Schematic diagram of water balance sub-model. Block arrows represent material fluxes of water. $AET$ is the actual evapotranspiration from the surface compartment (subscript $a$) and bulk compartment (subscript $b$), $P$ is precipitation, $AET_a$ is the evapotranspiration from the surface layer, $AET_b$ is the evapotranspiration from the bulk layer, $R_o$ is surface runoff, $FluxToSur$ is the flux between the surface and bulk layers, $z_a$ is the depth of the surface layer and $z_b$ is the depth of the bulk layer.

2.1.2 Evapotranspiration

Water is lost from the soil by evapotranspiration via the surface compartment and further water loss from the bulk soil can occur via evapotranspiration, drainage and runoff. In the original model of Deardorff's no surface runoff or deep drainage components were included as the model was only run for short periods when drying by evaporation (from a bare soil surface) was the dominant process. The modifications made here to include surface runoff and deep drainage in Deardorff's model are necessary as the model described here operates for a longer time period. Similar modifications to allow the model to be for longer time periods have also been made by Shao et al. (1996).
The loss or gain of water from the soil is via both the bulk soil layer as well as through the surface layer. Evapotranspiration (ET) is lost from both the surface layer and bulk soil layers. The partitioning of the water loss is done as a two-part process. The total ET is calculated from the reference evapotranspiration (ETo) and a crop factor (Kc). ETo is calculated using the Penman-Monteith equation for a well watered grass surface. This method is the current FAO standard (Smith et al., 1996) further discussion on this method for sugarcane can be found in (Attard et al., 2003). The maximum value of Kc has been found to be 1.25 in a number of studies on sugar cane (Attard et al., 2003). The first modifier of the evapotranspiration is to calculate the actual evapotranspiration (AET) for this we have used the ‘broken stick’ model proposed by Feddes et al. (1974) described by:

\[
AET = ET_o \cdot K_c, \quad \text{if } . \ s > . \ f_c / 2
\]

\[
AET = 2ET_o \cdot K_c \cdot . \ b / . \ f_c, \quad \text{if } . \ b = . \ f_c / 2
\]

where . \ s is the saturated water content of the soil and . \ f_c is water content at field capacity. This model ignores the decrease in transpiration associated with lack of aeration. The linear decrease in AET with water content is a simplification but for the purposes of this model this function is sufficient.

The amount of evapotranspiration extracted from the bulk layer is AET and the proportion of this AET derived from the surface layer is then calculated as follows. It has been found in a number of studies that more water is extracted from near the surface (Borg, 1980; McAneney and Judd, 1983) from these data a function for proportion of rooting depth (z/R) to proportion of water extraction (K_r) was derived;

\[
K_r = 1.23(1 - \exp(-1.8z / R))
\]

Here we will assume that z_b = R and z = z_o, and Kr is calculated with eqn (8). The proportion of the AET_o extracted from the surface layer is then given by:

\[
AET_o = ET_o \cdot K_c \cdot K_r, \quad \text{if } . \ s > . \ f_c / 2
\]

\[
AET_o = 2ET_o \cdot K_c \cdot K_r \cdot . \ b / . \ f_c, \quad \text{if } . \ b = . \ f_c / 2
\]

2.1.3 Drainage

A further departure from Deardorff’s model is that loss of water to deeper in the soil is considered to occur when the water content of the bulk soil layer is greater than field capacity. The rate of drainage (R_d) is given by:

\[
R_d = C_2 K_s \left( \frac{. \ b - . \ f_c}{. \ s - . \ f_c} \right)
\]

where C_2 is a constant. When C_2 = 1 this represents the free drainage boundary condition. Values of C_2 < 1 will be necessary when restricted drainage occurs, such as field drains etc, and C_2 = 0 is the no drainage boundary condition. If there are no other losses of water from the bulk layer this will result in an exponential decay in . \ b
with time. This is illustrated for a soil draining from saturation ($s = 0.5 \, \text{m}^3 \, \text{m}^{-3}$), with a field capacity ($FC$) of $0.35 \, \text{m}^3 \, \text{m}^{-3}$, $C_2 = 1$, $z_b = 1 \, \text{m}$ and $K_s = 0.1 \, \text{m day}^{-1}$ (Fig. 2).

**Figure 2.** Water content of bulk layer with time when draining from saturation with; $s = 0.5$, $FC = 0.35 \, C_2 = 1$, $z_b = 1 \, \text{m}$ and $K_s = 0.1 \, \text{m day}^{-1}$.

### 2.1.4 Runoff

In the model runoff occurs when the apparent water content ($\wedge \wedge$) of the bulk layer is $> s$. The depth of the water on the soil surface ($d_r$) is then simply the given by:

$$d_r = (\wedge \wedge - s)z_b$$

and the runoff rate ($Ro$) by (after Moore and Foster, 1990):

$$Ro = \frac{a}{l} d_r^m$$

where $a$ is a parameter reflecting the effects of slope and hydraulic roughness on flow, $l$ is the width of the discharging surface (see below) and $m$ is a parameter dependent on the type of flow, which may be laminar, turbulent or transitional. The values of $a$ and $m$ can be calculated for laminar and transitional flow if a number of other parameters are know (Moore and Foster, 1990). For turbulent flow the Manning-Strickler equation can be used:

$$a = \frac{\sqrt{S_p}}{n}, \quad m = \frac{5}{3}$$

where $S_p$ is the slope $[\text{L} \, \text{L}^{-1}]$ and $n$ is the Manning-Strickler coefficient $[\text{T} \, \text{L}^{-1/3}]$. The values of $n$ for various surfaces are given in Table 1.
Table 1. Values of the Manning-Strickler coefficient $n$ for various surfaces (Cote, 1999 unpublished).

<table>
<thead>
<tr>
<th>Surface</th>
<th>$n$ (m$^{-1/3}$ day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grass</td>
<td>$5.42 \times 10^{-3}$</td>
</tr>
<tr>
<td>Bare</td>
<td>$1.67 \times 10^{-3}$</td>
</tr>
<tr>
<td>Track</td>
<td>$0.83 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

The grass value will be close to that of a trash blanketed site and the burnt will lie somewhere between the bare and track values.

The width of discharge is taken as unity in this application. Otherwise the modelling will have to become a two-dimensional model to account for the partial wetting. This is beyond the application of the present model but is possible to implement.

The runoff model as presently implemented does not account for flux-induced runoff due to the precipitation rate exceeding the infiltration rate. This can be implemented using the time-compression approach of Salvucci and Entekhabi (1994). However, it is unlikely that rainfall intensity data will be available. This is a further development that is possible with this model.

2.2 Carbon Dynamics and Main Model

2.2.1 Carbon Loading of Soil

The amount of carbon applied to the soil is calculated from knowledge of; the yield of the cane crop and the harvesting method. A further possible development would be to include a multiplier to account for the effect of lodging of cane on harvesting efficiency. From the data gather by Rayment and Raymond (unpublished) they found that on average about of 0.26 Tonnes of sucrose ha$^{-1}$ yr$^{-1}$ of the sugar in the crop was lost during the harvesting process. This is equivalent to approximately 2.7% of the total crop yield (mass), but is probably an underestimate (G. Rayment, pers. comm.). For burnt cane a further 2.6% of the total crop yield is estimated to be lost during burning of the cane due to physical ejection of juice and exudation from the heated stalk (Foster and Irvin, 1981) and must be added to the amount lost during harvesting. For green cane harvesting the trash left behind represents approximately 12% of the total crop yield (Robertson and Thorburn, 2000) and the carbon content of this is a further input to the soil. The carbon content of all these components is approximately 40% of the dry mass and for the green cane the water content is approximately 70% (P. Bloesch, pers comm., 2003).

The initial carbon contents of the juice and trash pools are then determined as follows. For the juice component we have

$$JuiceC = Yield.(0.3).(0.027 + 0.026).(0.411)/10, \quad Burnt\ cane$$

$$= Yield.(0.3).(0.027).(0.411)/10, \quad Greencane$$ (14)
where $JuiceC$ is the carbon added to the soil in juice (kg C m$^{-2}$), $Yield$ is the cane yield (Tonnes ha$^{-1}$), and the other factors convert wet cane to dry mass, sucrose to carbon and Tonnes ha$^{-1}$ to kg m$^{-2}$. The trash component is calculated by:

$$TrashC = Yield \times (0.12) \times (0.3) \times (0.411) / 10$$  \hspace{1cm} (15)$$

where the factor 0.12 is from Robertson and Thorburn (2000). It may be useful to change this to a parameter that is inputted by the user which is an easy modification to make, as under some circumstances the trash may be $> 12\%$ of yield.

2.2.2 Degradation rates

The degradation rate is calculated using a function that is based on a separation of the variables into functions solely dependent on one variable (Cook, 2002). In this implementation the variables are; temperature, water content, degree of contact, and time. The functions used for each variable will be outlined below along with the supporting data obtained from the experimental program from which the function was derived. The degradation rate ($R$) is calculated with:

$$R = C \times (R_{\text{max}} \times r(t) + r_o) \times r(T) \times f(T) \times \text{Contact} / 0.8$$  \hspace{1cm} (16)$$

where $C$ is the amount of carbon from either trash or juice per unit area (kg-C m$^{-2}$) $R_{\text{max}} = r_o + a$ (see below for detail), $Contact$ is the contact function described below, the other functions are described below and the 0.8 is to account for the carbon used for cellular growth and repair.

Experiments were conducted to determine soil respiration as a function with time following amendment with addition of sugar trash or sugar juice. These experiments consisted of treatments where the soil was at three different water contents and the carbon amendments were incorporated to different degrees into the soil. Control treatments at each of the water contents where no additional carbon was added to the soil were also included.

2.2.2.1 Time function

The rate of decrease in the respiration rate ($r$, kg C day$^{-1}$) as a function of time ($t$) is well described by first-order kinetics (Cook et al., 2003a):

$$r(t) = r_o + a \times \exp(-b \times t)$$  \hspace{1cm} (17)$$

where $r_o$ is the approximate long time respiration rate (kg C day$^{-1}$), $(r_o + a)$ is the initial respiration rate (kg C day$^{-1}$) at $t = 0$ and $b$ is the time constant which determines the rate of decrease in respiration with time (day$^{-1}$). Experiments were conducted at different water contents and different degrees of incorporation of trash or juice into the soil. There was no consistent trend in $b$ with either degree of incorporation, carbon source (juice or trash) or water content (Cook et al., 2003b) and the overall mean value for $b$ is 0.09±0.06 day$^{-1}$. The values of $a$ and $r_o$ were effected by degree of incorporation and water content (Cook et al., 2003b), and these will be discussed in more detail below. Here we will discuss the effect of carbon source (juice or trash) on the value of $r_o$. 

9
The maximum treatment effect occurred when the soil was at its highest water content and the carbon amendment was fully incorporated. When the carbon amendment was juice the respiration was initially high compared to the control treatment and had decreased to almost that of the control treatment by 30 days (Fig. 3). However, given the small amount of carbon added it is still elevated compared to the control the value of \( r_0 \) was calculated to be 3 kg CO\(_2\)-C day\(^{-1}\) m\(^{-2}\) kg-C\(^{-1}\). This value takes into account the effects of the amount of substrate, temperature and water content on this basal respiration rate and in the model is called J_Min_Resp in the models parameter list.

Similar data for trash as the carbon amendment is shown in figure 4. By comparison with the juice data the respiration is elevated compared to the control but the amount of carbon added is much greater so \( r_0 \) is calculated to be 0.25 kg CO\(_2\)-C day\(^{-1}\) m\(^{-2}\) kg-C\(^{-1}\). In the model this parameter is called T_Min_Resp.

The maximum (initial) respiration rate when expressed in the same units (CO\(_2\)-C day\(^{-1}\) m\(^{-2}\) kg-C\(^{-1}\)) is for juice 36.4 and trash 6 kg CO\(_2\)-C day\(^{-1}\) m\(^{-2}\) kg-C\(^{-1}\). These rates are called in the model respectively J_Max_Resp and T_Max_Resp. We can clearly see that the carbon in the juice is consumed at about six times the rate of that in the trash when the amount of carbon added is taken into account.

![Figure 3. Comparison of respiration rate of CO\(_2\)-C with time for treatments with and without cane juice added at the rate equivalent to 0.2 Tonnes C ha\(^{-1}\). The regressions shown are for a first order kinetic reaction described by eqn (17).](image-url)
Figure 4. Comparison of respiration rate of CO$_2$-C with time for treatments with and without cane juice added at the rate equivalent to 4 Tonnes C ha$^{-1}$. The regressions shown are for a first order kinetic reaction described by eqn (17).

2.2.2.2 Temperature Function

Respiration experiments were carried out, with trash fully incorporated at a water content of approximately field capacity, at four temperatures viz 15, 24, 30 and 35°C. These experiments are well fitted by first order kinetic functions and from these the initial rate ($r_o + a$) was determined. These data were then fitted to the kinetic theory of Lloyd and Taylor (1994):

$$r(T) \cdot \exp\left[-\frac{E_o}{(T - T_o)}\right]$$

(18)

where $T$ is the temperature (K), $E_o$ is the initiation energy (308.6 K, Lloyd and Taylor, 1994) and $T_o$ is the base temperature (227.1 K, Lloyd and Taylor, 1994). The results show that eqn (18) fits the data very well (Figure 5).
Figure 5. Initial respiration rate with temperature and regression with eqn (18). The $r^2$ of the regression is 0.961.

Given the excellent fit eqn (18) was used as the temperature function in the model with values of $E_o$ and $T_o$ as given above.

The temperature as a function of time is calculated from the daily maximum ($T_{\text{max}}$) and minimum daily ($T_{\text{min}}$) temperatures using a sine function:

$$\sin\left(\frac{2\pi}{\tau}\right)(T_{\text{max}} - T_{\text{min}})/2 + (T_{\text{max}} + T_{\text{min}})/2$$

(19)

where $\tau$ is the period (1 day).

2.2.2.3 Water content function

Experimental data from the three experiments were normalised with respect to the saturated water content ($s$) and respiration rate data as follows. The saturated water content ($s$, m$^3$ m$^{-3}$) was estimated from the bulk density ($\gamma$, kg m$^{-3}$) using:

$$s = 1 - \gamma/2650$$

(20)

The normalised water content ($T$) is then given by:

$$T = \gamma/s$$

(21)
The respiration rate was normalised with respect to the initial respiration rate at the highest water content. These data were then plotted and a straight line was found to be the best fit (Fig. 6).

**Figure 6.** Normalised initial respiration rate versus normalised water content. Experiments 1 and 2 are trash treatments at two different sites and experiment 3 is the juice experiment. The regression is has an $r^2$ of 0.78.

The regression relationship is:

$$f(T) = 1.255T - 0.04$$  \hspace{1cm} (22)

Equation (22) is used in the model to modify the respiration rate with respect to the water content of the top layer. Although this function is not a great fit to the data, this function

2.2.2.4 Contact function

These experiments included a treatment associated with the degree of incorporation of either the trash or juice into the soil. This was included as it was thought to be a possible way of increasing the rate of breakdown of the trash or juice. The initial rate of respiration was normalised at each water content with respect to full incorporation. The trash treatments show that the respiration rate is reduced unless full incorporation occurs (Figure 7a). In comparison the partially incorporated juice gives similar respiration rate to the full incorporated, but surface application still results in a reduction in respiration rate (Figure 7b).
Figure 7. The effect of trash or juice incorporation on the initial respiration rate a) for trash and b) for juice. These are mean values of 6 measurements for the trash and 3 for the juice. The bars indicate one standard deviation.

From these results we incorporate a contact factor into the respiration function which has values of 1 for full and \( \frac{1}{2} \) incorporation of juice and 0.71 for surface applied, and 1 for full incorporation, 0.86 for \( \frac{1}{2} \) incorporation and 0.64 for surface applied trash.
2.2.3 Transfer of Carbon to Runoff Water

Experiments were carried out on trash collected from 1 m$^2$ of the surface of a cane field (4.2 kg fresh weight) immediately following harvesting. This was soaked in a drum containing 61.1 litres of water and the total dissolved oxygen (TOC) and biological oxygen demand (BOD$^5$) measured at three times. From this data the amount of carbon in the water as a proportion of the initial carbon and expressed per m$^3$ of water was calculated ($C_w$). $C_w$ was plotted against time (figure 8) and was found to be very well described ($r^2 = 1$) by:

$$C_w = d \cdot t^e$$  \hspace{1cm} (23)

where $d$ is a constant (kg-C$_{aq}$ kg-C$_s^{-1}$ m$^{-3}$ day$^{-e}$), the subscripts $aq$ and $s$ refer to the aqueous carbon and solid carbon respectively, and $e$ is a parameter. The rate constant for the rate of dissolution of carbon is obtained by differentiating eqn (23) with respect to $t$. This means that the rate of transfer of carbon to the water ($T_{Sol\_Rate}$) during a runoff event is calculated by:

$$T_{Sol\_Rate} = Trash.C.TWR.d\cdot t^{e-1}.Vol$$  \hspace{1cm} (24)

where $TWR = d \cdot e$, $RT = e - 1$, $t_E$ is the time since the start of the runoff event (day) and $Vol$ is the volume of runoff (m$^3$). Since the model works on a unit area $Vol$ in the model is the depth of runoff water, $d_r$.

![Figure 8. $C_w$ with time for trash soaking. The line is regression of eqn (23) and the parameters are $d = 2.52$ (kg-C$_{aq}$ kg-C$_s^{-1}$ m$^{-3}$ day$^{-e}$) and $e = 0.196$ with an $r^2 = 1$.](image)

A similar soaking experiment was carried out with burnt material and billets and collected over a 5 m$^2$ area immediately following harvest. This was soaked in a drum
containing 65 litres of water. $C_w$ was calculated as above for the trash and was equally well fitted by eqn (23) (Fig. 9). This is used to calculate the rate of transfer from the juice compartment in the model, but this may underestimate this rate as the juice is likely to dissolve faster. From runs with the model an increase in the rate of about 2 to 3 results in estimated BOD’s that are similar to those measured. The rate of carbon transfer ($J_{Sol\_Rate}$) is then similar to eqn (24):

$$J_{Sol\_Rate} = JuiceC_{JWR}t_{Sol}^{RJ}Vol.M$$

(eqn 25)

$JWR = d_e, RJ = e – 1$ and $M$ is the multiplier for sugar. The parameter $M$ in eqn (25) is a multiplier as the rate of transfer of sugar juice will be faster that suggested from the burnt cane trash and billet results. At present the value of $M$ this is set to 2.5.

![Figure 9. $C_w$ with time for burnt leaves and billets soaking. The line is regression of eqn (23) and the parameters are $d = 5.61$ (kg-C$_{aq}$ kg-C$_s^{-1}$ m$^{-3}$ day$^{-1}$) and $e = 0.245$ with an $r^2 = 0.9997$.](image)

To determine the value of $t_e$ the time at which a runoff event is initiated ($TD$) is determined using a defined event variable in ModelMaker. The value of $t_e$ is then simply calculated by $t_e = t – TD$.

### 2.2.4 Determining BOD in Runoff Water

The total carbon that has been transferred to runoff water ($WSC$) is determined in the model by:

$$WSC = \int_0^t (J_{Sol\_Rate} + T_{Sol\_Rate}) dt,$$

(eqn 26)
the integration of \( T_{\text{Sol} \_ \text{Rate}} \) and \( J_{\text{Sol} \_ \text{Rate}} \). However, we are conducting experiments to determine the rate of sugar dissolution. The same event timer that determines \( TD \) is also used to determine the amount of runoff than had occurred prior to this event (\( Ro_e \)). The volume of runoff in this particular event is then calculated as:

\[
Vol = RO(t) - Ro_e
\]  

(27)

where \( RO(t) \) is the cumulative runoff at time \( t \).

A similar method is used to determine the carbon transfer to runoff water. The concentration of carbon in the runoff water (\( TOC \)) is then calculated by:

\[
TOC(t) = 1000(WSC(t) - ESC)/Vol
\]  

(28)

where \( ESC \) is the amount of carbon in the water soluble carbon (\( WSC \)) storage compartment prior to the runoff event starting. The factor of 1000 is to convert from kg-C m\(^{-3}\) to mg L\(^{-1}\), which is the commonly used unit for TOC and BOD\(_5\). The BOD\(_5\) is finally calculated from the relationship obtained from the data collected during this project (Fig. 10).

**Figure 10.** Relationship between BOD\(_5\) and TOC. The linear regression is shown and is BOD\(_5\) = 1.73xTOC and has an \( r^2 = 0.983 \).

This completes the description of the calculation procedures within the model.
3. MODEL INITIATION AND DATA REQUIREMENTS

Within ModelMaker the integral equations are solved as an initial value problem at each time step and the Runge-Kutta is used for determining the time steps. The layout of the model is shown in figures 11 & 12.

Figure 11. Layout of the main model. The rectangular boxes are masses (integrals) the solid lines are mass fluxes (differentials), the elliptical boxes are variables, the hexagonal boxes are define variables and the double rectangular box is a sub-model.

Figure 12. Layout of the water balance submodel model. The rectangular boxes are masses (integrals) the solid lines are mass fluxes (differentials), the elliptical boxes are variables, the hexagonal boxes are define variables. The boxes labelled Switch On and Switch off are component event definitions where the values are changed dependent on the defined variable values. The box labelled Climate is a lookup table with values of the climate parameters.

The value of the yield needs to be entered into the Yield box (Fig. 11). The rest of the initial values in the main model are then obtained from the parameter table. Examples
of values for these parameters are listed below in Table 2. Also a screen capture of
the actual parameter table in BODOS is shown in Figure 13. Note, the value of \( \pi \) is
entered as this is not available otherwise in ModelMaker.

![Screen capture of parameter table from ModelMaker. The parameters, values and units are given in Table 2 below.](image)

**Figure 13.** Screen capture of parameter table from ModelMaker. The parameters, values and units are given in Table 2 below.

Most of the parameters in Table 2 are defined above except for the FCx, IWCx and Sat_x (where x is the layer, a or b), which are, respectively, field capacity, initial water content and saturated water content.
Table 2. Parameter table for BOD model in ModelMaker.

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The only other parameters that need to be inputted to initialise the model are:

The value of either 1 (for burnt) or 0 (for trash) needs to be entered in the Burnt defined value box in the Main model.

The climate data needs to be inputted into the climate table. This can be done by copying from a spreadsheet or text file into the climate table.

An example of the climate file for the Pimpama site, which is used as an example in the next section is shown in Appendix 1.

The only other data that needs to be inputted are the run options. These are set by clicking on the Model tab on the toolbar at the top and then the Run Options tab in the drop down menu bar. This brings up the input box shown below (Fig. 14).
The value of the start time (Start Value) is usually 0 (note the first time in the climate data table needs to be 0). The end time (Stop Value) may be inputted and the climate data must extend for at least this length of time. The number of output steps will determine how smooth the output is and needs to be about 10 times the end time to give reasonable values for the temperature function. The Random Seed should be left at the default value of 1.

The model can be run by clicking on the GO button, or clicking on the Model tab and then the run button.

4. OUTPUT

ModelMaker 3 provides convenient table generation and graphing facilities within it. In BODOS we have created 2 output tables and 4 graphs. The output tables are: Table of C mass, and Table of H2O & BOD. The first table gives the mass of carbon in the trash, juice, and WSC (water soluble carbon) compartments at each time step. The second Table, the cumulative amount of AET, P (precipitation), RO (runoff), DR (drainage) and W (water in bulk layer) as depth of water (m) per m², and the BOD in the runoff water (mg L⁻¹).

The available graphs are, BOD (BOD versus time), TrashC & JuiceC (trash and juice carbon versus time), and Depth of Water (water in bulk layer, maximum water depth for the bulk layer and water in surface layer versus time).
5. EXAMPLE

This example presents modelling of a site at Pimpama described in detail in Cook et al. (2003b) and Carlin et al. (2003). This site was green cane harvested on 6th September 2002 and a runoff event resulting from a small rainfall event occurred 51 days later. This runoff event is depicted in figure 14. The modelled results were found to be sensitive to the initial water content of the soil layers and the drainage modifier $C_2$. These parameters were adjusted to give similar modelled and measured cumulative runoff (Fig. 15). This sensitivity is due to the runoff event being small < 3 mm.

![Figure 15. Comparison of cumulative run off data from a field plot at Pimpama and the model.](image)

Comparison of the modelled BOD$_5$ with measured on a time basis shows extremely good agreement between the modelled and measured values (Fig. 16). However, this is spurious, as the two runoff samples were collected, near the start and end of the runoff event.
Figure 16. Comparison of measured BOD$_5$ in runoff and modelled BOD$_5$ for Pimpama site with time.

To overcome this the BOD$_5$ were plotted against cumulative runoff (Fig.17) this shows that the model has still done reasonably well in reproducing similar BOD$_5$ values at the measured runoff volumes. The model does seem to be giving reasonable predictions of BOD$_5$. However, in using this model the implications of the simplifications and assumptions need to be understood. These are: the simplifications in the water balance model of using only two layers and that runoff is only generated by overtopping of the soil water store, the estimation of the carbon inputs of juice and trash, and that the soaking experiments are representative of the transfer rates of carbon from the trash or juice to the dissolved phase.
6. SUMMARY

A model that predicts the BOD$_5$ in runoff water is presented. This model estimates the carbon applied to the soil from the sugar cane yield as juice and trash components. The amount of each component depends on the harvesting method, green cane or burnt. The rate of degradation of the carbon with time is based on time, temperature, water content and degree of contact between soil and carbon source. When runoff occurs some of the carbon is transferred to the water and the total organic carbon (TOC) of the water is related to BOD$_5$ by an empirical relationship.

A sub-model calculates the water balance using a nested two-bucket approach. This model uses physical parameters for the drainage and runoff sections. The transpiration and evaporation are considered to be related to the scaled root-length density, crop factors and potential evapotranspiration.

The model is documented here, so that it should be easy for a user to implement. The model gives reasonable predictions of BOD$_5$ when compared to limited experimental results, but needs further testing with other data sets.

7. ACKNOWLEDGEMENTS.

This work was part funded by CSIRO Land and Water and the CRC for Sustainable Sugar Production.
8. REFERENCES


**Appendix 1.** Climate Data, time, \( t \), (day), Precipitation, Precip, (m), Evaporation, Evap (m), maximum daily temperature, \( T_{\text{max}} \), \( ^\circ \text{C} \) and minimum daily temperature, \( T_{\text{min}} \), \( ^\circ \text{C} \).

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