

PREDICTING SUITABLE DAYS FOR FIELD MACHINERY OPERATIONS IN A WHOLE FARM SIMULATION

C. A. Rotz, T. M. Harrigan

ABSTRACT. *Accurate information on the days suitable for field operations is important in the design, development, and selection of efficient machinery systems for crop production. The number of days suitable varies widely with climate, soil characteristics, and type of operation. This information is normally difficult to obtain for a given location. A model was developed to predict suitable day information from long-term weather records and soil characteristics of a location. This model forms a component of a farm model where it is used in the simulation of the timeliness, productivity, and costs of machinery systems in crop production. Optional output provides annual, long-term average, and 80% and 90% probable values for the days suitable each month. The model was verified to predict suitable day information similar to field observations for recent years in northwestern Indiana and similar to long-term historical data for a few other locations across the Midwest. The number of suitable days predicted each month was moderately sensitive to some soil characteristics and highly sensitive to the tractability coefficients used to determine a suitable day. Recommended tractability coefficients were developed for spring and fall operations on various soil textures. Usefulness of the model was further demonstrated by determining the 80% probable number of suitable days each month in central Michigan using conventional, mulch, and no-till systems on clay loam, loam, and sandy loam soils. Incorporation of the suitable day model into a whole-farm simulation model provides a useful research and teaching tool for studying the influence of weather on the days suitable for fieldwork, the performance of field machinery operations, machinery effects and interactions with other parts of the farm, and the economics of production systems.*

Keywords. *Machinery management, Suitable days, Field working days, Farm model, Simulation.*

Owning and operating machinery remains one of the largest costs in crop production. Since the price received for agricultural produce has declined for a number of years in relation to the costs of production, producers continue to pursue lower cost and more efficient production systems. The development or selection of optimal machinery systems can help reduce costs while providing timely field operations that optimize the yield and quality of the crops produced.

Computer models have been developed to aid the selection of optimal machinery systems for farms. The major model types include static machinery selection algorithms (Rotz et al., 1983; Siemens et al., 1990) and dynamic simulation models (Harrigan et al., 1996; Rotz and Coiner, 2005). In each of these types, the number of days suitable for fieldwork is an important component in the selection and analysis of machinery systems. In order to predict the amount of work that can be accomplished, the time available within the optimal period for the required operation must be known. The time available varies considerably from year to year as weather conditions vary. Selection of the optimal machinery

set for long-term production on the farm depends upon accurate assessment of the days available for performing each field operation.

Over two decades from the mid-1960s to the mid-1980s, considerable effort was given to gathering information on the days suitable for agricultural field operations. Some studies recorded actual farm data, but most of the effort was in the development of models to predict suitable days from daily weather records. Several models were developed. They were similar in that soil moisture was tracked and some critical soil moisture condition was set to determine whether a given field operation could be performed on a given day (Rutledge and McHardy, 1968; Baier, 1973; Kish and Privette, 1974; Tulu et al., 1974; Elliott et al., 1977; Dyer and Baier, 1979; Rosenberg et al., 1982). In a more recent study, Cooper et al. (1997) used this approach with a more mechanistic soil model to determine the effect of climate change on soil workability and available workdays in Scotland. Differences among these models were the thickness and number of soil layers monitored in the soil profile and the critical soil moisture limits selected. Soil moisture was tracked in one to six soil zones or layers in the top 15 to 30 cm of the soil profile. Critical moisture contents were normally expressed in relation to the water-holding capacity of these soil zones, with values between 70% and 105% of field capacity used for different soil types and machinery operations. Rounsevell (1993) did a comprehensive review of the soil workability and suitable day models developed and applied in the United States, Canada, and Europe.

Some of the suitable days data developed in the 1970s was synthesized and published in the 1978 version of the Machinery Management Data of the ASAE Standards. These

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data have remained in those standards published each year since that time (*ASAE Standards*, 2003). These include data from actual weather records for central Illinois and Iowa and simulated values for southeastern Michigan, South Carolina, southern Ontario, and the Mississippi delta. These data have been widely used in the selection and analysis of machinery systems, and they have often been extrapolated to soils and climate conditions beyond those intended for their use. Therefore, there is a need for a tool that can readily develop suitable day information for essentially any location, field operation, and soil characteristics.

Our primary objective was to develop a component model for use in whole farm simulation that predicts the days suitable for field operations across a wide range in soil, crop, machinery, and weather conditions. A secondary objective was to synthesize the suitable day information generated by the model into output useful for other machinery selection models and applications.

MODEL DEVELOPMENT

The suitable day model was developed for use as a component of the Integrated Farm System Model. This whole-farm simulation model is a research and teaching tool for evaluating and comparing the long-term economic and environmental sustainability of production systems. This general tool can be used to evaluate crop, beef, and dairy farms. Machinery systems for tillage, planting, harvesting, and manure application can be evaluated along with many other aspects of farms. These include alternatives in cropping and grazing practices, feeding strategies, and manure handling methods.

INTEGRATED FARM SYSTEM MODEL

The Integrated Farm System Model is a simulation tool that integrates the many biological and physical processes on crop, beef, and dairy farms (Harrigan et al., 1996; Rotz and Coiner, 2005). Crop production, feed use, and the return of manure nutrients back to the land are simulated over many weather years. Growth and development of grass, alfalfa, corn, soybean, and small grain crops are predicted on a daily time step based on soil and weather conditions. Tillage, planting, harvest, and storage operations are simulated to determine resource use, timeliness of operations, crop losses, and nutritive changes in feeds. Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of the animal groups making up the herd.

Nutrient flows through the farm are modeled to predict potential nutrient accumulation in the soil and loss to the environment (Rotz and Coiner, 2005). The quantity and nutrient content of the manure produced is a function of the quantity and nutrient content of the feeds consumed. Nitrogen losses through volatilization, leaching, and denitrification are accounted to predict that available for crop uptake. A whole-farm balance of N, P, and K includes the import of nutrients in feed and fertilizer and the export in milk, animals, excess feed, and manure.

Simulated performance is used to predict production costs, income, and farm net return or profit for each year of weather (Rotz and Coiner, 2005). A whole-farm budget is used where investments in equipment and structures are

depreciated over their economic life, and the resulting annual costs are added to other annual expenditures and incomes determined for each year. By simulating several production alternatives, the effects of system changes are compared including resource use, production efficiency, environmental impact, and the net return to management. The distribution of annual values can also be used to assess the risk involved in alternative technologies or strategies as influenced by weather.

SUITABLE DAY COMPONENT

The suitable day component developed for the Integrated Farm System Model follows an approach similar to that used in several models developed in the 1970s (Rutledge and McHardy, 1968; Baier, 1973; Tulu et al., 1974; Elliott et al., 1977; Dyer and Baier, 1979; Rosenberg et al., 1982). Suitable days for fieldwork are predicted on a daily time step based upon soil moisture. Important components of this prediction include soil moisture, the soil moisture criteria for determining soil tractability, and the effect of crop residue. The major difference from previous models is that a more sophisticated soil model is used. This general soil model is used to determine both the tractability of field operations and the moisture available for the growth and development of each crop on the farm.

Suitable day information is linked to the machinery component of the farm model to determine the field operations that can be performed each day. The designated field speed, size, and other equipment characteristics of each machinery system are used to calculate an effective field capacity of the operation. The work done each day is determined until each operation is completed based upon this capacity and a user-specified number of hours available for fieldwork each day.

A distribution of the suitable days across months and years for each type of field operation is available as an optional output of the farm model. The number of days suitable for fieldwork each month of each year is provided. This information is then summarized over all simulated years to provide the suitable days each month at 50%, 80%, and 90% probability levels. The 50% probable number of days is the mean over the years simulated. The 80% and 90% probable values are determined for each month as the average number of suitable days minus the product of the *t* value and standard deviation of those values. The *t* values are set considering single-tailed probabilities of 0.2 or 0.1 for the 80% and 90% probability levels, respectively (Ott, 1993). For an 80% probability, *t* values range from 1.38 to 0.86 depending upon the degrees of freedom (number of years simulated). For a 90% probability, *t* values range from 3.08 for one year to 1.32 for more than 20 years. An 80% probability represents the minimum number of suitable days that can be anticipated in 8 out of 10 years. This probability level is often used in the design of field machinery sets to select the smallest machinery system that can complete field operations most years without a substantial timeliness loss (Rotz et al., 1983).

Soil Moisture Model

Soil moisture is modeled based upon the soil component of the CERES-Maize crop model (Jones and Kiniry, 1986). Precipitation, runoff, evapotranspiration, moisture migration, and drainage are tracked through time to predict the

moisture content in multiple layers of the soil profile. Soils are generally described as clay loam, loam, sandy loam, or loamy sand with deep, moderate, or shallow depths. Parameters used to describe soils include available water-holding capacity, surface albedo, evaporation and drainage coefficients, moist bulk density, runoff curve number, and the organic matter, silt, clay, and sand contents. With these characteristics, the lower limit of extractable water (permanent wilting point), drained upper limit (field capacity), and saturated moisture contents are determined (Jones and Kiniry, 1986). Soil moisture is tracked using the gravimetric content on a dry-mass basis.

The soil is modeled in four layers where all layers use the same soil characteristics. The four layers consist of three relatively thin layers near the surface with thicknesses of 30, 45, and 75 mm. The fourth layer extends from the 150-mm depth to the bottom of the soil profile or the crop rooting depth, whichever is first limiting. The maximum depth or bottom of the profile is the assigned available water-holding capacity divided by the difference between the drained upper and lower limits of the soil. Typical rooting depths of 1.5 m are used for corn and soybeans, 1.2 m for small grains, 1.8 m for alfalfa, and 0.8 m for grass.

Moisture entering the top soil layer is precipitation plus irrigation water minus runoff. Daily precipitation is obtained from the weather data provided as model input. If irrigation is used, additional water is added in 20 mm increments on days when the soil moisture drops below 60% of that at field capacity. Water runoff is calculated using a U.S. Soil Conservation Service (SCS) runoff curve number where the amount of runoff is related to the amount of precipitation and the moisture content in the top 45 cm of the soil (Jones and Kiniry, 1986). The incoming moisture fills the top layer until its drained upper limit is met. Remaining moisture moves through the first layer to fill the second layer. This filling effect occurs for each of the layers until the soil profile (all four layers) is filled to the drained upper limit. At this point, moisture drains to the underlying ground water and is unavailable to the crop.

Moisture is extracted from the soil by evapotranspiration, i.e. water loss through evaporation from both soil and plant surfaces. Soil evaporation is determined using the two-stage method developed by Ritchie (1972). In stage 1, soil evaporation is limited by energy. In stage 2, soil evaporation declines as a function of time from the beginning of this stage. Plant transpiration is a function of the solar radiation level, ambient temperature, crop albedo and leaf area index, and soil moisture availability (Jones and Kiniry, 1986). Moisture from soil evaporation is subtracted from the upper layer of the soil profile and plant transpiration is taken from the lower layers. Transpiration moisture is divided among layers with 15% taken from the second layer, 25% taken from the third, and the remainder taken from the larger lower layer. Moisture removal from each layer is limited by the lower limit of extractable moisture for that layer.

Unsaturated moisture flow among the soil layers allows moisture to migrate toward equilibrium. Moisture moves up or down through the soil profile when the moisture level in a layer is greater than that in an adjacent layer. Moisture flow rate is a function of the soil water diffusivity and the amount of difference in soil moisture level between layers (Jones and Kiniry, 1986).

The link between soil moisture and the growth and development of the crop is modeled using a water stress factor (Jones and Kiniry, 1986). This factor varies from 0 to 1 where 1 represents no stress on the crop. Values are less than 1 below the critical soil moisture where stress begins. This critical soil moisture is normally set at half the available water-holding capacity in the root zone. Below this level, the water stress factor declines in proportion to available soil moisture toward zero at the lower limit of available moisture. Plant transpiration and the associated moisture uptake decline in proportion to the decrease in the water stress factor.

The initial soil moisture content in the spring is set on a spring thaw date. The thaw date is determined from an accumulation of degree-days where the degree-day value for a given day is the average daily temperature above freezing ($^{\circ}\text{C}$; Tulu et al., 1974). Until a maximum average daily temperature of 7°C is reached, the accumulation of degree-days is divided by 6. If an average daily temperature of less than 0°C occurs, the accumulation is reinitialized. The soil is considered thawed when 14 degree-days have accumulated.

The initial soil moisture following the spring thaw is normally set at field capacity or the drained upper limit moisture content. In a dry climate or following a relatively dry winter season, this initial moisture is reduced. Total precipitation for the first 90 days of the year is divided by the available water-holding capacity of the soil. If this ratio is less than one, the initial soil moisture content is reduced in proportion toward a minimum level at 30% of field capacity.

Machine Tractability

Soil moisture conditions are predicted for each day of the year before, during, and after the growth and development of each crop. For spring operations, suitable days are determined considering a fallow soil; whereas, days suitable for summer and fall operations are determined using the soil under or following the growing crop. A day is considered suitable when the soil moisture conditions meet or exceed the tractability requirements of the equipment.

The suitability of a given day is decided by comparing the moisture in the upper three soil layers (surface to 30 mm, 30 to 75 mm, and 75 to 150 mm) to preset limits for each layer. The moisture level in the remainder of the soil profile does not directly affect tractability. Soil moisture limits for tractability vary by soil texture and the type of field operation performed. Soil is generally considered tractable or suitable for tillage operations when soil moisture to the depth of tillage is near 95% of field capacity (Rutledge and McHardy, 1968), but higher levels are appropriate for surface or non-soil engaging operations. Higher moisture is normally more acceptable for coarse soils than fine-textured soils, and higher moisture may be tolerated when there are opportunities to alleviate soil compaction prior to spring planting. Remedial activities to alleviate compaction may include fall tillage under drier soil conditions, winter freezing and thawing cycles, and tillage operations the following spring.

Soil moisture limits for tractability are assigned by the model user as tractability coefficients. This coefficient is the ratio of allowable moisture in a soil layer to that at field capacity (drained upper limit). The limit for the top two layers is normally set a little lower than that for the third layer because tractability is most sensitive to surface conditions. Tractability coefficients also vary with the type of field

operation and the time of the year. A slightly drier soil is usually required for spring tillage, manure injection, and planting than is acceptable for fall tillage or spring surface spreading of manure.

Six tractability coefficients are assigned as parameters for each soil type. Coefficients are set for spring tillage and planting operations, fall tillage and planting operations, and fall harvest and manure spreading operations. Coefficients for the top layers and the third soil layer are specified by the model user for each of these three major types of operations. Increasing these coefficients relaxes the soil moisture constraints allowing more suitable days for fieldwork.

A few field operations are simulated that do not fall within the three designated types. These are surface spreading of manure in the spring and manure injection in either the spring or fall. For simplicity, the tractability coefficients for surface spreading in the spring are determined by increasing the spring tillage coefficients by 1.5%. Injection of manure in the spring uses the coefficients for spring tillage, while manure injection in the fall uses the fall tillage coefficients.

During daily simulations, moisture levels in the upper three soil layers on any given day are compared to the appropriate tractability coefficients to determine if any field operations can occur. Soil moisture must be below the critical limits for all three layers to permit a given operation. An array of values is established for the three types of operations over 365 days. For each operation and each day, the full day is designated as suitable (value of 1) or not suitable (value of 0) for fieldwork. During the simulation, a given operation can only be performed on days designated as suitable for that operation when labor and tractor time are available beyond that required by competing operations on the farm.

Due to the lack of within-day weather information, the model was developed to work in whole day units. In practice, partial days may sometimes be available prior to or following rain. Through proper calibration of the model in whole-day units though, the long-term simulation results should be similar to those obtained considering fractions of a day. The model user sets the hours available for fieldwork during that full-day period. For a crop farm, operations may be performed for 12 h or more per day; however, on a dairy farm only 6 to 8 h/d may be available for field operations due to other farm operations and tasks that compete for the machinery operator's time.

Tillage Type and Residue Cover

Crop residue on the soil surface slows moisture evaporation and thus influences the days suitable for fieldwork. Residue cover primarily reduces stage 1 soil evaporation by reflecting solar radiation, reducing wind velocity and temperature at the soil surface, and providing a barrier or resistance to moisture migration (Bond and Willis, 1969, 1970; Smika, 1983; Brun et al., 1986; Aase and Tanaka, 1987). The reduction in stage 1 drying has been shown to be nearly linear with increasing residue cover until the soil is completely covered (Bond and Willis, 1969). Further residue continues to reduce drying but at a diminished rate. Experimental studies have measured 40% to 60% reductions in soil moisture loss under heavy residue covers compared to bare soil (Bond and Willis, 1969, 1970; Brun et al., 1986; Aase and Tanaka, 1987). For our model, residue effects were

determined with a linear reduction in stage 1 evaporation of 0 to 50% with increasing residue cover from 0 to 100%.

Residue cover is influenced by the previous crop grown and the type of tillage system used. Three major tillage systems were defined as conventional, mulch, and no-till. Conventional tillage represented the use of a moldboard plow where the soil was inverted leaving no residue on the surface. Mulch tillage represented the use of a chisel plow or similar tool, which left a major portion of the residue on the surface. For mulch tillage of corn and small grain crops, residue was assumed to cover 50% of the soil surface in the fall with 40% coverage in the spring. For no-till systems of these crops, all residue remained on the surface providing 90% coverage in the fall and 80% coverage in the spring. For soybean residue, coverage was 50% of that assumed for corn and small grains.

MODEL EVALUATION

The suitable day component of the Integrated Farm System Model was evaluated to assure reasonable prediction of the days available for field operations. This evaluation included a comparison of predicted and actual annual records of suitable days, a comparison of predicted long-term monthly suitable days to published values, and a sensitivity analysis to test the effect of parameter changes on the predicted number of days suitable for fieldwork.

ANNUAL RECORDS

Days suitable for fieldwork are routinely monitored in nine regions across the state of Indiana. Data for each region and the state average are published each year by the Indiana Agricultural Statistics Service (IASS, 2004). These data are obtained through individual observers within each region of the state. They monitor the weather and farm activities within their region to designate each day as suitable or unsuitable for field activities. As such, these data represent a general accounting of the days available for fieldwork. For example, a day may be suitable for activities such as corn harvest or manure spreading when the soil conditions would not permit tillage operations. Thus, these data represents days that are suitable for any operation to occur. Available days may be overestimated for specific operations such as primary tillage.

As a check on the accuracy of the model, suitable days were simulated for Lafayette, Indiana, and compared to field observations for the northwestern region of the state. Suitable days predicted for each month from April through November were compared to those observed over the five weather years of 1999 to 2003. The soil was modeled as a deep silt loam, typical of the soils in this region. The soil was described as 60% silt, 30% clay, and 10% sand with an available water-holding capacity of 210 mm. Moist bulk density was set at 1.36 g/cm³, and the whole profile drainage rate coefficient was 0.35. Tractability coefficients were set at 0.93 for the surface layers and 0.95 for the third layer for spring operations and 1.05 for the upper three soil layers for summer and fall operations.

With these tractability coefficients, the model predicted similar suitable days as those observed over the 40 months (5 years of 8 months per year; fig. 1). A good correlation ($r = 0.88$) between simulated and observed suitable days was found. For most months, the difference between simulated and observed values was 2 d or less, but larger differences of

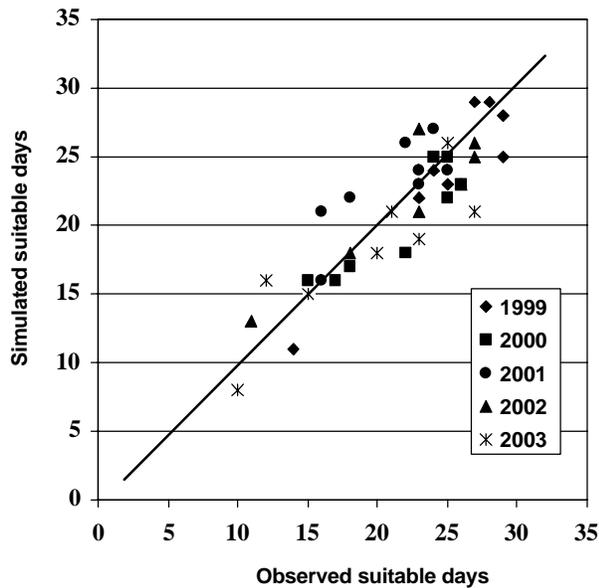


Figure 1. Model-predicted suitable days for fieldwork by month (April to November) compared to observed values over five years of weather (40 months) in northwest Indiana. Observed values were obtained from the Indiana Agricultural Statistics Service (2004).

up to 4 d occurred for a couple months. Considering that the simulated data were for a specific location and soil and that the observed values covered a whole region, some difference can be expected. We observed that for months where

discrepancies occurred between simulated and observed values for the northwestern region, simulated values were often similar to those observed in surrounding regions. This further illustrates the effect of weather variability and its impact on suitable days across a region. Overall, this comparison supports that the model can predict suitable day information representative of that experienced on actual farms.

LONG-TERM DATA

As a second step in the evaluation process, long-term monthly values of simulated suitable days were compared to those published in the Machinery Management Data of the ASAE Standards (ASAE Standards, 2003). The farm model was used to simulate farms in central Illinois, central Iowa, and southeastern Michigan. At each location, suitable day information was simulated for the production of a corn crop using conventional tillage. Historical weather data were used to simulate a location within each region with the soil described to represent a typical soil of that region (table 1). Farms at each location were simulated for years 1961 to 1975. These years were selected to best represent the weather years originally used as a basis for the ASAE data. These data were developed around this time; however, actual weather years were not reported. Suitable days each month were derived from the ASAE data by multiplying monthly average values for the portion of days suitable by the number of days in the month. No adjustment was made for nonworking Sundays and holidays.

Table 1. A comparison of the suitable days for fieldwork determined from 50% and 90% probability levels for working days published in the Machinery Management Data of the ASAE Standards (ASAE, 2003) to that simulated by the Integrated Farm System Model.

Location, Soil, and Data Source	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Annual
Central Illinois ^[a] , Deep silt loam soil ^[b]										
ASAE data, 50%	4.3	13.5	18.3	20.1	22.3	25.4	21.9	22.6	19.2	168
Simulated, 50%	2.7	13.5	18.5	20.4	23.5	24.1	20.3	24.9	19.9	168
ASAE data, 90%	0.0	4.8	10.9	13.2	16.4	21.4	16.2	16.4	14.1	113
Simulated, 90%	0.0	3.5	11.5	11.8	18.6	19.2	14.1	19.5	12.6	111
Iowa ^[c] , Deep loam soil ^[d]										
ASAE data, 50%	0.0	13.5	20.8	20.7	24.5	25.7	22.2	23.3	23.1	174
Simulated, 50%	1.7	15.7	19.9	20.5	24.4	25.9	21.5	24.8	21.7	176
ASAE data, 90%	0.0	9.0	14.6	15.6	19.8	22.9	15.9	17.4	17.7	133
Simulated, 90%	0.0	8.4	14.2	14.7	19.2	21.6	14.2	19.7	14.7	127
Southeast Michigan ^[e] , Medium clay loam ^[f]										
ASAE data, 50%	0.0	6.0	18.9	20.7	23.3	22.9	20.1	16.4	7.5	136
Simulated, 50%	1.8	11.5	18.4	19.3	22.0	21.7	20.8	16.7	11.7	144
ASAE data, 90%	0.0	0.0	9.9	12.6	16.1	16.4	9.9	6.5	0.9	72
Simulated, 90%	0.0	5.3	11.8	12.4	16.9	17.0	12.0	7.1	1.1	84

^[a] Simulated using Springfield weather data, 1961 to 1975.

^[b] Soil consisted of 60% silt, 30% clay, and 10% sand with a moist bulk density of 1.3 g/cm³, an available water-holding capacity of 210 mm, and a drainage rate coefficient of 0.35. Tractability coefficients were 0.90 and 0.94 for the upper and lower soil layers with spring operations and 1.0 and 0.99 for the upper lower soil layers in summer and fall operations.

^[c] Simulated using Ames weather data, 1961 to 1975.

^[d] Soil consisted of 68% silt, 30% clay, and 2% sand with a moist bulk density of 1.3 g/cm³, an available water-holding capacity of 210 mm, and a drainage rate coefficient of 0.35. Tractability coefficients were 0.90 and 0.93 for the upper and lower soil layers with spring operations and 1.02 and 1.03 for the upper lower soil layers in summer and fall operations.

^[e] Simulated using Coldwater weather data, 1961 to 1975.

^[f] Soil consisted of 45% silt, 45% clay, and 10% sand with a moist bulk density of 1.15 g/cm³, an available water-holding capacity of 130 mm, and a drainage rate coefficient of 0.35. Tractability coefficients were 0.90 and 0.93 for the upper and lower soil layers with spring operations and 0.97 and 0.98 for the upper lower soil layers in summer and fall operations.

Simulated and ASAE data are compared in table 1 for the months of March through November for both 50% and 90% probability levels. Simulated average (50% probability) values compared very closely to those from ASAE with a high correlation at each location ($r = 0.97$ to 0.99). Monthly average values predicted by our model were normally within 2 d and often within 1 d of the ASAE values. Differences were slightly greater at the 90% probability level, but the correlation between ASAE and simulated values was still high ($r = 0.96$ to 0.98).

SENSITIVITY ANALYSIS

As a third step in the evaluation of the suitable days component, an analysis was done to measure the sensitivity of simulated suitable days to changes in the soil characteristics and tractability coefficients. Soil characteristics included soil depth, texture, drainage rate, moist bulk density, and organic matter content. Depth was varied by changing the available water-holding capacity from 210 mm for a deep soil to 126 mm for a moderate depth and 63 mm for shallow soil. Soil texture was manipulated by adjusting the sand content from 10% in a clay loam to 20%, 44%, and 89% for loam, sandy loam, and loamy sand soils, respectively. Silt content in the four soils was 45%, 70%, 50%, and 6%, respectively with the remainder being clay. Drainage rate was adjusted by reducing the whole-profile drainage rate coefficient from 0.35 to 0.175. Bulk density and organic matter content were each increased by 10%. This analysis was based upon corn production in Iowa (1966 to 1990 weather for Des Moines) using conventional tillage practices.

Tractability coefficients must be set considering the size and type of operations performed and the soil's ability to withstand wheel traffic or tillage operations. In general, a more sandy soil can support traffic at higher moisture levels relative to the available water-holding capacity of the soil than finer textured soils. In this analysis, however, soil texture and the tractability coefficients were evaluated independently. Tractability coefficients were both increased and decreased by 2% relative to the values assumed in the base analysis. In the base analysis, coefficients of 0.92 and 0.94 were used for the upper (top 76 mm) and lower (76 to 150 mm) soil layers in the spring with 0.99 and 1.0 used for the upper and lower soil layers in the fall.

Sensitivity was measured by comparing the total days suitable for fieldwork in the spring (March through June) and fall (August through November) seasons. These seasons were observed separately because the parameter changes tended to have different and sometimes opposite effects on the days suitable in the spring and fall. Seasonal differences occurred primarily due to different soil moisture conditions. In the spring, the soil was normally at or near field capacity throughout the profile with the only moisture loss due to evaporation at the surface. At the end of the growing season, the growing crops depleted much of the soil moisture. Rain moisture was more quickly absorbed into the soil to recharge the soil moisture throughout the profile.

Sensitivity was measured using a sensitivity coefficient. This coefficient was determined by dividing the average percentage change in the predicted suitable days by the average percentage change in the input parameter. This provided a dimensionless number where a value near or greater than 1 indicated high sensitivity. A value in this range

Table 2. Sensitivity of simulated suitable days for fieldwork to changes in soil characteristics and tractability coefficients.

Soil Characteristic	Suitable Days ^[a]		Sensitivity Coefficient ^[b]	
	Spring	Fall	Spring	Fall
Base simulation ^[c]	62.8	78.0	—	—
Medium depth (AWHC ^[d] reduced 40%)	60.0	78.1	0.091	-0.003
Shallow depth (AWHC reduced 70%)	48.3	81.1	0.242	-0.036
Silt loam (20% sand, 70% silt, 10% clay)	62.8	72.8	0.000	-0.103
Sandy loam (44% sand, 50% silt, 6% clay)	62.5	68.1	-0.004	-0.108
Loamy sand (89% sand, 6% silt, 5% clay)	26.5	59.6	-0.509	-0.168
Drainage rate (reduced 50%)	61.0	69.2	0.04	0.18
Bulk density (increased 10%)	52.5	81.7	-1.88	0.49
Soil organic matter (increased 10%)	59.6	77.5	-0.55	-0.07
Tractability coefficient (increased 2%)	66.5	86.0	2.95	4.88
Tractability coefficient (decreased 2%)	50.9	71.4	10.59	4.33

[a] Average days available for fieldwork using conventional tillage practices in spring (March to June) and fall (August to November) simulated using 1966 to 1990 weather for Des Moines, Iowa.

[b] Sensitivity coefficient is the average change in simulated suitable days divided by the average change in the input characteristic. This is a dimensionless number where a value near or greater than 1 indicates high sensitivity and values of less than 0.1 indicate relatively low sensitivity.

[c] Deep clay loam soil (10% sand, 45% silt, and 45% clay contents) with available water-holding capacity of 210 mm, drainage rate coefficient of 0.35, moist bulk density of 1.2 g/cm³, organic matter content of 3.1%, and tractability coefficients of 0.92 and 0.94 for the upper and lower soil layers in the spring and 0.99 and 1.0 for the upper and lower soil layers in the fall.

[d] AWHC is available water-holding capacity.

meant that at least a 1% change in the predicted suitable days occurred for each 1% change in the input value. Values of less than 0.1 indicated relatively low sensitivity.

Simulated suitable days were relatively insensitive to the depth or available water-holding capacity of the assumed soil, particularly in the fall season (table 2). As soil depth was reduced, the number of days suitable for fieldwork decreased in the spring and increased a small amount in the fall. Soil texture had a greater effect, particularly in the fall season. In the spring, soil texture did not have much effect until the sand content became very high (table 2). In the fall, increases in sand content caused moderate reductions in the predicted days available for fieldwork. This occurred because the low moisture holding capacity of these soils was more readily saturated by rainfall. This does not mean that one should expect fewer suitable days in sandy soils. Greater tractability coefficients can be assumed for these soils, which more than offset this effect of texture alone.

Of the remaining soil characteristics, simulated suitable days were most highly sensitive to soil bulk density. A small increase in bulk density caused a large decrease in available days in the spring and an increase in the days available in the fall. Assumed organic matter content had a similar but less dramatic effect in the spring only (table 2).

Simulated suitable days were most sensitive to the tractability coefficients used to represent the machinery and soil requirements. Relatively small changes in these coefficients caused very large changes in the predicted days available. A decrease in these coefficients had a slightly

greater effect than increased values in the spring season (table 2).

MODEL APPLICATION

The Integrated Farm System Model is used to evaluate the long-term production, environmental impact, and profitability of farm production systems. Production alternatives include many individual and combinations of changes in crop and pasture production, feed harvest and storage, animal feeding and maintenance, and manure handling. Inclusion of the suitable day component provides a tool that is particularly useful for the analysis of machinery systems. This whole-farm model can simulate the performance and calculate the cost and economic return of a farm using a given machinery system. A 25-year simulation provides a long-term analysis including timeliness effects on crop yield and quality and other indirect costs due to the interaction of the machinery system with other production components (Harrigan et al., 1996). By comparing various machinery options, an economically optimum machinery set can be determined for a given farm as well as the economic loss encountered using less than optimum machinery.

The model can also be used to generate suitable day information for other applications. Model output includes available field working days for 50%, 80%, and 90% probabilities of occurrence. Such information can be used in machinery management to supplement data published in the *ASAE Standards* (2003). The model provides data for the

Table 3. Recommended tractability coefficients by operation, soil layer, and soil type.

Soil Type	Spring Tillage ^[a]		Fall Tillage ^[a]		Fall Harvest ^[b]	
	Upper ^[c]	Lower ^[d]	Upper	Lower	Upper	Lower
Clay loam	0.92	0.94	0.99	1.00	1.03	1.01
Loam	0.94	0.96	1.02	1.03	1.04	1.02
Sandy loam	0.96	0.98	1.03	1.05	1.06	1.04
Loamy sand	1.00	1.00	1.04	1.04	1.08	1.06

^[a] Includes manure injection.

^[b] Includes surface spreading of manure.

^[c] Top 75 mm of soil profile.

^[d] 75- to 150-mm depth in soil profile.

specific weather, soil, and equipment used in a given application, and thus should provide more accurate assessment and selection of machinery for a particular farm.

TRACTABILITY COEFFICIENTS

When the farm model is used to study suitable days for fieldwork and closely related issues, the selection of appropriate tractability coefficients is important. As demonstrated above, the values selected have a large impact on the number of days predicted as suitable. Tractability coefficients should be set considering the type of operation performed and the texture of the soil. Based upon our experience with the model and the work of others (Rutledge and McHardy, 1968; Baier, 1973; Tulu et al, 1974; Elliott et al., 1977; Rosenberg et al., 1982), a set of generally recommended values is given in table 3.

Table 4. Predicted field working days (80% probability) for three tillage systems (levels of crop residue cover) and three soils in south central Michigan.^[a]

	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Conventional tillage ^[b] and planting operations ^[c]										
Clay loam	8.7	18.4	17.3	22.6	19.0	14.7	12.7	3.8	0.0	117
Loam	10.6	19.8	18.5	23.0	20.2	15.3	15.6	6.8	1.8	132
Sandy loam	11.7	21.0	19.7	23.7	21.6	17.2	17.8	9.0	4.4	146
Conventional tillage surface operations ^[d]										
Clay loam	9.9	19.8	19.0	24.7	22.7	18.2	18.3	8.6	1.8	143
Loam	11.0	20.4	18.8	23.4	21.4	16.6	17.2	8.8	3.6	141
Sandy loam	12.4	21.7	20.4	24.5	22.4	19.0	19.4	11.8	7.7	159
Mulch tillage ^[e] and planting operations										
Clay loam	7.3	16.6	15.2	22.0	17.3	13.7	11.5	2.7	0.0	106
Loam	8.8	18.1	16.6	22.6	19.4	14.9	14.7	6.0	1.3	122
Sandy loam	10.2	19.4	18.2	23.3	21.1	16.6	16.6	8.0	3.6	137
Mulch tillage surface operations										
Clay loam	8.3	18.0	16.6	24.2	21.9	17.5	16.8	7.0	1.1	131
Loam	9.1	18.3	17.2	23.3	20.3	15.6	16.4	7.5	2.6	130
Sandy loam	11.0	20.1	18.8	24.0	22.1	18.2	18.6	10.5	6.6	150
No-till ^[f] planting operations										
Clay loam	5.7	14.2	12.3	21.3	16.4	12.9	10.0	1.8	0.0	95
Loam	6.8	14.8	13.6	22.4	18.0	14.1	13.0	5.1	1.1	109
Sandy loam	8.5	17.6	15.5	23.1	20.0	15.8	15.5	7.1	3.3	126
No-till surface operations										
Clay loam	6.8	15.4	13.7	23.8	20.5	16.8	14.7	6.0	0.8	119
Loam	7.4	16.1	14.2	22.7	19.5	14.9	14.6	6.2	1.6	117
Sandy loam	8.9	17.8	16.5	23.8	21.3	17.6	17.5	9.8	6.2	139

^[a] Simulated using Lansing, Michigan weather from 1966 to 1990.

^[b] Conventional tillage uses a moldboard plow leaving no residue cover in the fall or spring.

^[c] Includes soil injection of manure.

^[d] Includes grain harvest operations and surface spreading of manure.

^[e] Mulch tillage uses a chisel plow or similar tool leaving 50% residue cover in the fall and 40% cover in the spring.

^[f] No-till uses no tillage leaving 90% residue cover in the fall and 80% cover in the spring.

Model users are encouraged to evaluate the suitable days predicted for specific simulated conditions, and if necessary, adjustments of the tractability coefficients and other soil parameters can be made. When heavy equipment is used or the soil is known to readily compact, lower coefficients should be used. Likewise, for light equipment or soils with an established sod or heavy residue cover, higher coefficients may be acceptable. Other factors that may have a small effect on tractability include tire type, size, and pressure and the use of machines with rubber or steel tracks. Enhancement of soil structure through long-term use of no-till production or the use of controlled traffic lanes may also warrant small increases in the tractability coefficients used. Such adjustments must be made based upon long-term experience with these specific conditions.

SOIL TYPE AND RESIDUE COVER

To demonstrate the use of the model, suitable day information was generated for central Michigan using Lansing weather from 1966 to 1990. Predicted suitable days for each month of the crop production season are shown in table 4 for three tillage systems on three major soil types. Suitable days are given for both soil tilling operations and surface operations such as grain harvest and manure spreading.

Soil type or texture had a greater effect on the suitable days for tillage operations than on surface type operations with a slightly greater effect in no-till systems relative to conventional tillage (table 4). With conventional tillage, switching from clay loam to loam or from loam to sandy loam each increased the number of suitable days an average of about 12%. For no-till systems, these changes in soil texture increased suitable days by about 15%. These results compare well to previous studies where differences in soil texture caused 10% to 15% changes in the number of days suitable for field operations in the Midwest (Parsons and Doster, 1980; Rosenberg et al., 1982) and a 20% (4 to 5 d/mo) increase comparing a sandy soil to a clay loam in Ontario (ASAE Standards, 2003). For surface operations, clay loam and loam soil textures provided similar numbers of suitable days, but with sandy loam soils, the number of days suitable for fieldwork again increased about 15% (table 4).

Little information is available on the effect of tillage system or residue cover on days suitable for fieldwork. The simulation results indicate that as tillage allows more residue to remain on the surface, the number of suitable days decreases (table 4). On a clay loam soil, shifting from conventional to mulch tillage or from mulch to no-till each created about a 10% decrease in the number of suitable days with a little less decrease on a sandy loam soil. The effect of tillage system was greatest in the spring where wet soils dried more slowly under the residue. Although less time was suitable for fieldwork in mulch and no-till systems, less time is also needed. A single pass with a no-till planter, can be completed in much less time than that required for a typical series of operations with conventional tillage.

MODEL AVAILABILITY

The Integrated Farm System Model is available from the Internet home page of the Pasture Systems and Watershed Management Research Unit (<http://pswmru.arsup.psu.edu>). The program should operate on computers that use any Microsoft Windows® operating system. To obtain a copy of

the program, the software section of the home page can be accessed where instructions for downloading and setting up the program are provided. The program includes an integrated help system and reference manual with detailed documentation of the model.

CONCLUSION

The Integrated Farm System Model can predict suitable day information for field machinery operations for a wide range in locations and soil conditions. This whole-farm model uses a suitable day component model along with other farm components to simulate the performance and predict the economic and environmental sustainability of production systems. Optional output provides annual, long-term average, and 80% and 90% probable values for the days suitable for fieldwork each month, which can be used in machinery selection algorithms and other machinery management analyses. A sensitivity analysis of the suitable day component model indicated that the number of days predicted as suitable for fieldwork was moderately sensitive to some soil characteristics and highly sensitive to the tractability coefficients used to determine a suitable day. Recommended tractability coefficients are provided, which may be adjusted to represent specific machinery and soil conditions.

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