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SIMULATION OF
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By

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ABSTRACT

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By

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The dairy forage system model (DAFOSYM) was expanded to evaluate tillage and manure management alternatives for Michigan dairy farms. Sub-models were added to predict draft and power requirements for tillage, planting and manure hauling. A soil moisture balance and daily time-step were added to predict suitable days for major field operations. Labor scheduling sub-models were added to allow varying the length of workday and number of simultaneous field operations. Through simulation, the long-term performance, cost and net return for three tillage and four manure handling systems were compared on 60, 150, 250, 400 and 800-cow representative dairy farms. The analysis included all factors of harvest, storage, feed and animal production including manure production, storage and application, tillage, planting, crop growth and machinery use. Mulch-till was the most economical tillage system and increased net return from \$15-\$39/cow-yr compared to conventional tillage. Modified no-till improved timeliness and reduced fuel and labor use by 50% compared to

conventional tillage, but those savings were offset by higher seed, chemical and fertilizer costs. Manure irrigation increased net return \$20-\$30/cow-yr over slurry injection on most farms. Slurry injection tended to delay tillage and planting unless additional labor and equipment were available to allow simultaneous manure hauling, tillage and planting. These delays reduced corn grain and silage yields and increased feed costs as much as \$24/cow-yr when conventional tillage was used. The greatest net return related to manure handling was associated with short-term storage and daily hauling if manure nutrient value was included. Net return ranged from minus \$342/cow-yr with slurry injection and conventional tillage on the 60-cow farm to \$558/cow-yr with daily hauling and mulch-tillage on the 800-cow farm.

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1. INTRODUCTION

Agriculture makes an important contribution to Michigan's economy. Cash receipts from crops, livestock and livestock products were nearly $3.24 billion in 1993 (MASS, 1994). Michigan ranked seventh nationally in milk production with nearly 2.45 billion liters (5.4 billion lbs) worth more than $715 million produced on the state's 5,000 dairy farms. Crop, dairy and livestock production were concentrated in the southern half of the lower peninsula where more than 80% of the cattle and calves, 98% of the hogs, pigs and poultry and 95% of all corn, wheat, soybeans and dry beans were produced.

Many changes in tillage and planting equipment have occured during the past 15 years. Conservation tillage practices are replacing moldboard plowing and conventional seedbed preparation on an increasing number of crop acres. Tillage tool components that allow a range of control over the amount of crop residue left on the soil surface and combination tillage tools that combine multiple tillage operations are now commonly used. Tillage practices that leave crop residue on the surface throughout the year reduce runoff and wind and water erosion and also offer an opportunity to reduce costs and labor requirements. However, concerns regarding soil compaction, odors and the inability to incorporate manure have slowed the adoption of these production practices on livestock farms.

A mature dairy cow creates about 54 kg (120 lb) of manure per day (MWPS, 1985; ASAE, 1993g). Manure properly managed is a valuable source of crop nutrients, but poorly managed manure is a potential source of water pollution. Many farmers object to the problems associated with manure application including soil compaction, uneven and slow application rate, introduction of weed seeds and the need for additional tillage for incorporation. Because of these problems, commercial fertilizers largely replaced manure as the primary source of crop nutrients and in many cases manure is spread with little regard to it's nutrient value or impact on the environment.

In recent years, the introduction of larger farms and more intensive livestock operations has brought crop production and manure management practices under closer scrutiny. Major environmental concerns include manure odors and the possibility of surface and groundwater contamination. State and Federal legislation has been enacted to protect the environment from both point and nonpoint pollution. At the Federal level, the National Pollutant Discharge Elimination System (NPDES, Sec. 401) focuses on water pollution from large livestock operations. The Coastal Zone Act Reauthorization Amendments of 1990 (CZARA) are being designed to protect surface water quality. The Conservation Compliance provision of the Food Security Act (FSA) will be fully implemented by 1995 and will deny farm program benefits to farmers not following approved conservation plans. More than a dozen State laws have been enacted to protect surface water quality (MDNR, 1993). The Michigan Right to Farm Act (P.A. 1981, No. 93) was adopted and amended in 1987 (P.A. 1987, No. 240) to protect the environment and to protect crop and livestock producers from nuisance suits if they follow recommended manure management practices regarding soil testing and nutrient management, timing and method of application, record keeping and containment of contaminated runoff (Michigan Agriculture Commission, 1992).

Protection of the environment and safe and efficient manure utilization involves changes in both farm structures and management practices. A combination of short term storage (≤2 months) and frequent hauling is preferred for most Michigan herds (Connor et al., 1989). This is a low cost system, but it may not be the best system for all farms. Short-term storage with frequent hauling requires fields available year around for spreading, a steady supply of labor and frequent incorporation of spread manure to minimize runoff and maximize manure nutrient use (Sweeten et al., 1983; Holmes and Klemme, 1989). The greatest nutrient losses in runoff water are expected where manure is spread on melting snow or frozen soil covered with ice (Klausner et al., 1976; Steenhuis et al., 1981) so some researchers recommend that manure be stored rather than spread on frozen ground (Minshall et al., 1970; Phillips et al., 1981).

Long-term manure storage with subsurface injection effectively minimizes odors and runoff and conserves nutrients but this system is expensive and concentrates labor for manure handling in the already busy period in the spring prior to planting and in the fall after harvest.

Tillage and manure storage and handling systems vary greatly in labor and machinery requirements, cost, compatibility with the environment and other aspects of the farming system. The challenge for dairy farmers is to manage these systems in a cost effective and environmentally safe manner. Crop and livestock production represents a set of interacting processes that must be considered to establish systems that serve both economic and environmental objectives. An analysis of the many interactions of manure management with other operations and processes on the dairy farm requires a systems approach (Schulte and Krocker, 1976).

Linear programming (Coote et al., 1976; Safley et al., 1977) and mixed integer programming (Amir and Ogilvie, 1977) have been used to evaluate dairy waste management systems. These studies optimized systems based on annual net cost. Burney et al. (1980a,b) used network analysis to analyze the annual cost, labor and energy requirements of major components of dairy manure management systems. In Michigan, Garsow et al. (1992) integrated information from various manure and farm financial management programs in an analysis of the economic impact of environmental control measures for dairy farms. Borton et al. (1995) used simulation to compare the long-term performance of semi-solid, slurry and liquid manure handling systems.

These studies revealed information regarding the costs and interactions of major components of dairy waste management systems. The need exists, however, for a more comprehensive analysis of tillage and manure handling systems which includes all factors of harvest, storage, feeding, animal production, and manure handling. Such an analysis requires a model which integrates the effects of weather, machinery, labor and other relevant factors on tillage, planting, harvest, manure storage and handling, and feeding of the dairy herd. A simulation model of the dairy forage system called DAFOSYM (Rotz et al., 1989) provides a basis for such a model. The model was previously used to evaluate a variety of dairy forage systems including the use of hay preservatives on high-moisture hay (Rotz et al., 1992), the benefits and costs of round bale hay storage (Harrigan et al., 1994), and dairy manure handling systems (Borton et al., 1995).

1.1 OBJECTIVES

A comprehensive analysis was conducted using the dairy forage system model DAFOSYM to compare tillage and manure handling systems on representative dairy farms. Specific objectives were to:

1. Develop parameters for implement draft, power requirements, speed and depth of operation for conventional, mulch-till and modified no-till tillage and planting equipment.
2. Develop sub-models in DAFOSYM which integrate the effects of weather, machinery, labor and other relevant factors on manure application and conventional and conservation tillage and planting of corn and alfalfa.
3. Analyze the costs and labor requirements of representative tillage and manure handling systems which include all major interactions from harvest through manure application, tillage and planting.
4. Compare the economics and performance of representative tillage, planting, manure storage, handling and land application systems on representative 60, 150, 250, 400 and 800-cow Michigan dairy farms.

2. LITERATURE REVIEW

2.1 ECONOMICS OF MANURE MANAGEMENT SYSTEMS

The close proximity of non-farm, rural residents to livestock operations has lead to frequent disputes between farm and non-farm residents. Complaints of excessive odor and surface and ground water contamination have become common (Ackerman and Taylor, 1985; Barth et al., 1982; Van Kleeck and Bulley, 1985; Brynildson 1989; Thelen, 1992; Harvey and Lohr, 1992). In some cases, public and private nuisance statutes have been brought to bear against livestock producers (George et al., 1985; Harvey and Lohr, 1992). Livestock producers have found that environmental concerns have created a more restrictive, tightly regulated and costly operating environment (Barth et al., 1982; Harvey and Lohr, 1992).

Animal waste management and pollution control costs have been shown to be regressive; the highest per unit costs are imposed on the smallest producers (Johnson et al., 1973; Van Arsdall and Smith, 1974; Garsow et al., 1992; Leatham et al., 1991). Leatham et al. (1991) examined the impact of compliance with Texas water quality laws on dairy profitability and estimated additional costs for 300 and 720 cow dairies to be $81 and $60 per cow-yr, respectively. Bennett et al. (1991) compared lagoon and above-ground tank storage systems within the context of Missouri waste management regulations and Clean Water Act provisions. Compared to short-term storage, the lagoon system increased milk production costs \$0.18 to \$0.27/hL (\$0.40 to \$0.60/cwt) and an above-ground liquid tank increased costs more than \$0.45/hL (\$1/cwt).

In Michigan, Good et al. (1973), Johnson et al. (1973) and later Garsow et al. (1992) examined the economic impact of environmental control measures for dairy farms including mandatory control of surface runoff, prohibition of winter spreading, subsurface injection of liquid slurry or immediate incorporation of solid waste. Each reported that control measures increased costs but did not increase revenue. Garsow et al. (1992) predicted a negative return on investments in manure storage and injection equipment and estimated a drop in net farm income of \$118/cow-yr for a 60 cow herd and \$37/cow-yr for a 250 cow herd compared to short-term storage with daily haul.

Equipment ownership and operating costs for several manure storage and land application systems have been reported (Johnson et al., 1973; Good et al., 1973; Moore and White, 1983; Maschhoff and Muehling, 1985; Burney et al., 1980a, 1980b; Bennett et al., 1991; Garsow et al., 1992; Borton et al., 1995; Bennett and Fulhage, 1994). The lowest costs were associated with short-term storage and daily hauling and the greatest with long-term liquid storage. Manure handling costs increase significantly with distance hauled (Borton et al., 1995). The use of a nurse tanker is economical for transport distances greater than 1 km (Maschhoff and Muehling, 1985; Borton et al., 1995). The most rapid and profitable transport and application system when hauling 9½ million L (2½ million gal) of liquid swine manure an average of 10 km (6.2 mi) was two nurse tankers for transport and a single vacuum tanker for land application (Maschhoff and Muehling, 1985).

2.2 MANURE STORAGE AND HANDLING SYSTEMS

The choice of manure handling system depends in part on the amount of bedding used, length of storage and the amount of water added. When only a small amount of bedding and little additional water is added, manure is about 12%-14% dry matter (DM, wet basis) and can be handled as a semi-solid. When manure is stored for long periods, water from precipitation, lot runoff, parlor wash water and other water sources increases the moisture content of the stored manure. Water use with an automatic prep stall can be about 34 L/cow-day (9 gal/cow-day) with additional water needed for cleaning the bulk tank, parlor floor and other areas (MWPS, 1985). The addition of about 60 L/cow-day (16 gal/cow-day) will dilute the manure from a semi-solid (12%-14% DM) to a slurry (8%-10% DM) for tank wagon transport. The addition of 115 L/cow-day (30 gal/cow-day) creates a dilute slurry (5%-7% DM) suitable for liquid irrigation.

2.2.1 Manure Storage Systems

Manure storage facilities range from flat slabs for solid manure to above ground glass-lined tanks for slurry and liquid storage. Above ground roofed storage has been used successfully for comfort stall arrangements where large amounts of bedding are mixed with the manure (Tenpas et al., 1972; Loudon and

Bickert, 1983). Drained (picket dam) storage provides a means of removing rain water from uncovered solid storage systems (Loudon and Bickert, 1983). Above ground storage tanks may be preferred where earthen storage cannot be used because of space constraints, high groundwater, unstable subsoil or for aesthetic reasons (Loudon and Bickert, 1983) but earthen pits provide the most cost effective long-term storage (Garsow, 1992). Long-term manure storage provides for a flexible spreading schedule, timely use of manure as fertilizer and efficient use of equipment and labor (Moore and White, 1983).

A floating crust of bedding and organic material on the surface of a stored slurry helps minimize odor (MSU, 1990), but environmental hazards related to manure storage remain a concern. Potential problems involve both surface and groundwater contamination. Research has been conducted to evaluate sealing mechanisms, infiltration rates and seepage from existing earthen storage ponds (Davis et al., 1973; Chang et al., 1974; Clark, 1975; Collins et al., 1975; Ritter et al., 1980; Dalen et al., 1983; Barrington et al., 1987a, 1987b). Soil sealing of an earthen basin was the result of physical, chemical and biological processes (Davis et al., 1973; Chang et al., 1974; Barrington et al. 1987a, 1987b). A small amount of seepage was reported in some cases (Sewell et al., 1975; Clark, 1975; Dalen et al., 1983), but after initial sealing there was usually little effect more than a few meters from the edge of the basin (Sewell et al., 1975, Collins et al., 1975; Ritter et al., 1980). There was little correlation between initial soil hydraulic conductivity and final manure infiltration rates (Chang et al., 1974; Barrington et al., 1987a).

Minnesota recently revised their standards for agricultural waste storage ponds because of concerns regarding seepage from earthen structures (Brach et al., 1992). Conditions were established whereby, with a credit for manure sealing, compacted soil liners would limit infiltration rates to 10^{-7} cm/sec. It was thought that seepage could occur through macropores, cracks caused by freezing and drying of the liner or through earthworm casts. It was also thought that excessive seepage could occur prior to sealing and seals that were broken when the pond was emptied would have to re-form when the pond was refilled. And, if physical sealing of soil pores was the primary sealing mechanism, inadequate sealing might occur when storing contaminated runoff of low solids content such as milking parlor waste water.

Michigan recommendations for earthen basin seepage control are to use liners that meet specifications and guidelines outlined in the USDA-SCS Field Office Technical Guides (MSU, 1990). Conditions were established whereby, with a credit for manure sealing, compacted soil liners limit infiltration rates to 10^{-7} cm/sec. In most situations, unlined earthen pits are not suitable and supplemental pit liners are suggested. Suitable liners included flexible membranes, bentonite, high swell clay materials or concrete.

2.2.2 Solid Manure Systems

In northern climates, most solid systems are associated with stanchion barns (Loudon and Bickert, 1983). Solid manure storage is used where manure dries or enough bedding is added to make it a stackable solid (Loudon and Bickert, 1983; MWPS, 1985; ASAE, 1993h). Total solids of 20% or more are required for a stacking system if organic bedding materials are used (Holmes, 1989). On most dairy farms calf pens, maternity pens and young stock housing are bedded and that material is handled as a solid even though manure from the milking herd is stored and handled as a slurry or semi-solid (Loudon and Bickert, 1983). The investment in specialized structures and equipment is low for solid systems since the manure and spent bedding are handled with conventional bucket loaders and end gate or flail type spreaders (Burney et al., 1980a, 1980b; Moore and White, 1983; Holmes and Klemme, 1989; Garsow, 1992; Borton et al., 1995). Waste water, including parlor wash water, lot runoff and manure drainage must be handled apart from the solid fraction (Holmes, 1989).

The characteristics of stacked manure have been reported by Cramer et al. (1973) and Converse et al. (1975). Based on 454 kg (1000 lb) live weight, average manure production including bedding (4 kg/d, 8.7 lb/d) was 0.05 m^3/d (1.8 ft^3/d) with an average density of 3.77 kg/m^3 (60.3 lb/ft^3) and total solids of 16.9% (Converse et al. 1975). The average in-place volume was about 22% less than the volume of manure collected indicating shrinkage during storage due to the separation of liquids and solids. The solids content when removed from storage was about 21%.

2.2.3 Semi-solid Manure Systems

Most of the new dairy barns built in Michigan are of free stall design. Manure from most free stall barns can be handled as a semi-solid unless additional water is added. Semi-solid manure has excess liquids drained off and some bedding added to increase solids content (MWPS, 1985; ASAE, 1993h). Manure with total solids of 10-15% is suitable for direct loading to a box or V-tank spreader (Sweeten et al., 1983). Semi-solid and solid manure can generally be handled out of the same facility and with the same set of equipment (Loudon and Bickert, 1983; MWPS, 1985). Box type spreaders are used primarily for solid and semi-solid manure and V-bottom spreaders are used primarily for semi-solid and slurry manure (ASAE, 1993j). Sand-laden manure with total solids of 40% or more can be handled as a semi-solid but considerable storage and handling problems may develop (Wedel and Bickert, 1994).

Drained storage has proven suitable in northern climates for short-term storage of free stall manure and longer-term storage of more heavily bedded free stall manure (Loudon and Bickert, 1983). Drained storage such as picket dam structures allows rain water to drain from uncovered storage thus maintaining the handling characteristics. But drained storage does not reduce the moisture content of manure in storage (Loudon and Bickert, 1983; MWPS, 1985) and additional facilities are required to contain and handle contaminated runoff.

Phillips (1980) compared semi-solid manure hauling and land application systems for a 150-cow dairy in Ontario, Canada. Manure averaging 14.3% DM was loaded with a front-end loader and hauled with a box spreader. The system was then modified and manure at 12.9% DM was loaded from storage with a liquid manure conveyor and hauled with a spreader tanker. The hauling rate was faster for the tanker than the box spreader due to faster loading and unloading rates.

2.2.4 Slurry and Liquid Manure Systems

Manure can be handled as a liquid if additional water is added. Common sources of dilution water are precipitation, lot runoff and milking parlor waste water. Dilution to 8-10% is recommended for tank or retention pond storage and spreading with a slurry tanker (ASAE, 1993h). Both slurry and thin slurries (liquid) are agitated prior to removal from storage to create a homogeneous material for land application (ASAE, 1993j). Slurry manure is typically hauled from storage with closed tanker spreaders and can be either surface applied or injected below the soil surface (ASAE, 1993j). Disadvantages of long-term storage with tanker spreading include the high initial cost of the storage structure (Moore and White, 1983; Holmes and Klemme, 1989; Garsow, 1992; Borton et al., 1995), soil compaction from large tractors and spreader tankers (Culley and

Patni, 1987) and odor emission (Sweeten et al., 1983; Holmes and Klemme, 1989).

Dilute slurries can be applied through irrigation systems. Several systems for liquid manure irrigation have been described (MWPS, 1985; Brodie, 1989). Semi-solid manure with 10-15% solids can be pumped through irrigation equipment using special pumps and gun nozzles (MWPS, 1985; Brodie, 1989), but for traveling gun irrigation, dilution to 4-7% solids is recommended (Sweeten et.al, 1983; ASAE, 1993h). Liquid irrigation systems have higher throughput capacity than tank wagons, require less labor (Melvin, 1979; Borton et al., 1995) and field access is not restricted when soils are too wet to support heavy tractor and spreader loads. Liquid irrigation of manure reduced costs compared to slurry spreading with long-term storage (Borton et al., 1995), but over-application, wind drift and odor transport are potential problems. Irrigation of sand-laden manure is not recommended since sand tends to separate and obstruct the lines (Wedel and Bickert, 1994).

2.3 ODOR NUISANCE

Manure management practices have contributed to offensive odor emissions from livestock production facilities. The most common source of odors are storage, treatment and land application areas. The objective of odor control efforts is to reduce the frequency, intensity, duration and offensiveness of odors and to manage the operation in a way that creates a favorable perception of the operation (MSU, 1990). Factors influencing odor are site selection, design of the manure handling components and the operation and management of the waste facility.

Proximity to neighbors is the most important factor determining which odor control procedures are needed (MSU, 1990; ASAE, 1993f). Consideration of neighbors is recommended to minimize nuisance complaints. The most remote locations require the least intensive management and least expensive technology. Wind dissipates odors and carries odor away from nearby neighbors. Manure should be injected or incorporated by tillage soon after spreading. Odors are reduced by spreading fresh rather than decomposed manure. Facilities and animals should be kept clean and storage and treatment systems should be designed for the operation.

2.4 TILLAGE SYSTEMS DEFINED

A tillage system defines a sequence of operations that manipulate the soil to enhance seed germination and crop growth. Typical operations in a crop production system include tilling the soil, planting, harvesting, chopping or shredding residue and applying pesticides and fertilizers (Dickey et al., 1992a). Tillage systems can be defined by objective or by the major tillage implements used. In Michigan, a typical conventional tillage system includes chopping or disking corn residue after harvest, applying fertilizer or manure, and then tilling the soil with a moldboard plow. Spring tillage includes disking and field cultivating to incorporate manure and prepare a seedbed. Conventional tillage systems leave almost no crop residue on the soil surface after planting.

Conservation tillage defines by objective a wide range of tillage systems. The primary objective of conservation tillage is to minimize wind and water erosion. Tillage system strategies to reduce erosion include: 1) protecting the soil with crop residue or growing plants, 2) increasing surface roughness, 3) increasing soil permeability, and 4) a combination of the three (Dickey et al., 1992a). Mulch-till includes all conservation tillage systems other than no-till. A wide range of tillage operations can be used in a mulch-till system as long as enough residue cover remains for erosion control. No-till is a conservation tillage system which leaves residue from the previous crop undisturbed on the soil surface throughout the year. The only tillage is a narrow seedbed cut by a coulter on the planter. Strip-till or zone-till is similar to no-till except that rather than using a single coulter on the planter, a gang of coulters (2 or 3) is used to till a wider seedbed (15-30 cm, 6-12 in.).

2.5 ECONOMICS OF TILLAGE SYSTEMS

The major costs influenced by tillage system selection are related to machinery and herbicides (Siemens and Doster, 1992). Both labor and machinery costs decrease as the amount of tillage or the number of tillage operations decrease. Estimated labor costs for a 405 ha (1,000 ac) corn-soybean farm in central Illinois were reduced by 30% and machinery costs by 25% with a no-till system compared to chisel and moldboard plow based systems (Siemens and Doster, 1992). No-till required less equipment, labor and horsepower than more intensive tillage systems.

Herbicide costs increase as tillage is reduced (Siemens and Doster, 1992). In Illinois, typical herbicide costs for corn production range from about $25-$37/ha ($10-$15/ac) with a moldboard-chisel system and $37-$62/ha ($15-$25/ac) with a no-till system. In Michigan, no-till fields frequently require additional herbicides for grass control in the first year of a crop in the rotation (Kells, 1994). Slug damage may also increase insecticide costs or decrease yields in no-till fields (Landis, 1994). Corn and alfalfa seeding rates are often increased 5%-10% in no-till fields to compensate for insect loss or reduced emergence in no-till conditions.

2.6 DRAFT OF TILLAGE AND PLANTING EQUIPMENT

Draft information is frequently used in machinery management to calculate power requirements of tillage and seeding operations. Farm managers and consultants use draft or power data to match tractors with implements and to estimate fuel requirements. Farming system computer models often require draft and power data to: 1) select farm machinery; 2) simulate the performance of farming systems; and 3) evaluate the performance of alternative farming systems. Accurate information on draft requirements is needed to create valid models.

Many changes in tillage and planting equipment have occured during the past 15 years. Conservation tillage practices are replacing moldboard plowing and seedbed tillage on an increasing number of crop acres. Tillage tool components that allow a range of control over the amount of crop residue left on the soil surface and combination tillage tools that combine multiple tillage operations are now commonly used (Siemens et al., 1992). Where seedbed tillage is reduced or eliminated, the planter or drill becomes the most important piece of equipment used. Many planters are now designed to cut through surface residue and in some cases to till a zone of soil for the seed furrow. Drafts for these new tillage and seeding implements are different from those published in the current ASAE Standards (1993a). An update of the ASAE draft data is required to more accurately represent current tillage and seeding practices.

2.6.1 Subsoilers

Deep tillage operations such as subsoiling are not annual tillage operations on most farms. But soils that are naturally compact or that have been compressed by heavy vehicle traffic on wet soil may benefit from deep tillage. If the problem lies below the normal tillage zone (20 cm, 8 in.), subsoiling may be helpful.

Subsoiler draft is affected by soil texture, strength and moisture, tillage depth, operating speed and subsoiler geometry. Since subsoilers are designed to penetrate and shatter dense, high strength soil layers, draft tends to be highly variable. Draft in clay soils can be more than twice that in sandy soils (Nichols and Reaves, 1958; Frisby and Summers, 1979; Trouse and Reaves, 1980; Wildman et al., 1978). Curved (parabolic) or inclined subsoil shanks typically create 10% to 20% lower draft than vertical shanks at the same depth (Nichols and Reaves, 1958; Smith and Williford, 1988; Upadhyaya et al., 1984). Garner et al. (1987) reported greater draft in soils with a shallow B-horizon. Subsoiler draft is reported as a positive linear function of depth (ASAE, 1993a; Garner and Wolf, 1981; Upadhyaya et al, 1984) and quadratic with respect to speed (Owen, 1989; Upadhyaya et al., 1984).

Tillage tines shatter soil at an angle from a point just above the tine tip to the soil surface (crescent failure). The angle of crescent failure varies but generally ranges from 20°to 45° from vertical (Cooper, 1971; Spoor and Godwin, 1978; Koohestani and Gregory, 1985; Gregory and M'Hedbhi, 1988). Below a critical depth, soil only flows forward and sideways (lateral failure) around the point, compacting soil in the area of the point without increasing soil disturbance (Spoor and Godwin, 1978). The critical depth is a function of subsoiler point geometry. Tines of similar width and rake angle have about the same critical depth. The critical depth with a narrow subsoiler point is typically about 30 cm (12 in.; Cooper, 1971) but is likely deeper in clay than sandy loam soils (Owen, 1988) and, in a given soil, deeper in friable than in wet and plastic conditions (Spoor and Godwin, 1978).

Winged attachments are often added to conventional, narrow subsoiler points to increase soil shatter. Wings increase both the critical depth (Owen, 1988; Spoor and Godwin, 1978) and the amount of soil disturbed (Spoor and Godwin, 1978; Ahmed and Godwin, 1983). Spoor and Godwin (1978) measured draft and area disturbed with conventional and winged (30 cm, 12 in.) points at different depths. When winged and narrow points were operated above the critical depth, the winged attachments more than doubled the disturbed area with only a 30% increase in draft. When operated below the critical depth of the narrow point, soil disturbance with the winged point was more than three times that of the narrow point with only a 10% increase in draft. Reeder et al. (1992) reported that 25 cm (10 in.) wings increased draft about 70% and 35 cm (14 in.) wings more than doubled the draft of a 5 cm (2 in.) point in a silt loam soil.

2.6.2. Liquid Manure Injectors

Direct soil injection of liquid manure conserves nitrogen and greatly reduces the odor associated with land application. Subsurface injection of liquid slurry is possible with up to 12% solids (Sweeten et al., 1983). A winged injector can inject almost twice the volume at a given depth as a narrow injector (Godwin et al., 1985). Winged injectors also distribute the manure over a wider area and decrease the potential for root inhibition and nitrogen losses (Schmitt and Hoeft, 1986). Winged injector points reduce draft requirements by creating more void space and permitting shallower injection than possible with narrow points (Godwin et al., 1976; Negi et al., 1978).

Liquid manure injector draft data are not included in the current ASAE data. Winged injector (30 cm, 12 in.) draft ranging from 1.5 kN in loose sand to 6 kN in clay loam was reported by Negi et al. (1978; 10 to 15 cm, 4 to 6 in.) depth. In a firm clay soil, draft of 5 to 6.2 kN at a depth of 20 cm (8 in.) was reported by Laguë (1991). Godwin et al. (1985) reported a draft of 5.4 kN at a depth of 13 cm (5 in.). Hann et al. (1987) reported a higher draft (1.9 kN) in the wheel track of a loaded tanker (800 gal., 3,028 L) than behind an empty tanker (1.1 kN) or an umbilical injector (1 kN). Scarborough et al. (1978) cited Horsfield (1974) indicating that compared to surface spreading, slurry injection at 20 cm (8 in.) with a narrow point required 13.4 kW (18 hp) per injector in addition to tanker rolling resistance.

2.6.3 Moldboard Plows

Moldboard plow draft data (N/cm^2 of the cross-section of tilled soil) are published for several soil textural groups ranging from sand to clay loam (ASAE, 1993a). Draft is described as a positive linear function of depth and quadratic with respect to speed. The Standard notes that soil moisture and specific gravity affect plow draft but the relationship is not quantified.

A model to predict moldboard plow draft utilizing soil moisture and strength was proposed (Eradat Oskoui and Witney, 1982) and tested (Eradat Oskoui et al., 1982). Draft was calculated as a function of soil cone index, soil moisture, soil specific weight, depth and width of tillage, plow speed and plow tail angle. When related to local meteorological data, the proposed model predicted draft better than previous models.

Bowers (1989) reported a wide range in draft both between and within soil textural groups. Differences within a textural group were presumably due to varying soil moisture and strength. Frisby and Summers (1979) found that predicted draft based on the ASAE Standard was high but within 10% of measured values for clay and loam soils. Summers et al. (1986) evaluated the effects of speed and depth on moldboard plow draft in clay loam and silt loam soils in Oklahoma and reported that measured data was closely estimated by the ASAE Standard. The draft data reported by Summers et al. (1986) confirmed the linear increase of draft with depth and the quadratic relationship with speed described by ASAE.

2.6.4 Chisel Plows

Compared to a moldboard plow, a chisel plow can cover a field faster, requires less power, creates no back or dead furrows and can be managed to leave significant amounts of crop residue on the soil surface. The rough surface of a fall chisel plowed field traps snow and moisture and helps protect the soil from wind and water erosion.

Draft is generally found to be a linear function of both depth and speed (Summers et al., 1986; Kydd et al., 1984; Gregory and M'Hedbhi, 1988) but draft has also been reported to be a quadratic function of depth (ASAE, 1993a; Grisso et al., 1994). The current ASAE data for chisel plows are not consistent with other implement data reported across soil textural groups. Unlike the moldboard plow and disk harrow, draft is higher for medium than fine textured soils.

Chisel plow point selection affects soil shatter, soil inversion, residue cover after tillage (Dickey et al., 1992b) and draft (Gregory and M'Hedhbi, 1988). Straight, 5 cm (2 in.) points shatter less soil and bury less residue than 7.5 cm (3 in.) or 10 cm (4 in.) twisted shovels. Wide sweeps are sometimes used to undercut weeds and loosen soil without burying surface residue. Gregory and M'Hedhbi (1988) reported that chisel plow draft should vary with the cross-sectional area of the furrow formed during tillage. The cross-sectional area formed by a chisel point is trapezoidal (Willatt and Willis, 1965; Koohestani and Gregory, 1985) with the bottom width approximated by the width of the chisel point. Based on the cross-sectional area described by Koohestani and Gregory (1985) and a 30° crescent failure, chisel draft with a 10 cm (4 in.) point will be about 15% greater and a 5 cm (2 in.) point 15% less than with a 7.5 cm (3 in.) point.

2.6.5 Disk Harrows

Disks harrows and combination tillage tools using disk gangs are among the most commonly used tillage implements. Disk harrows are used for primary tillage, seedbed preparation, weed control and incorporation of manure, fertilizers and herbicides. In the past, tandem disks typically had less mass per unit width, smaller diameter blades and a narrower blade spacing than offset disks. Tandem disks were generally used for secondary or light primary tillage while offset disks were used for heavy primary tillage. However, in recent years large tandem disk harrows similar to offset disks in mass, blade size, blade spacing and primary tillage capabilities have become common (Krishnan, 1988). The assumed difference in draft between tandem and offset disk harrows used in the past is no longer justified.

Many factors affect disk harrow draft including gang angle, mass per blade, blade type and spacing, operating depth and travel speed (Gill et al., 1981; Gill et al., 1982; Schafer et al., 1991; Sommer et al., 1983). Draft data for disk harrows is reported by ASAE (ASAE, 1993a) with draft expressed as a function of implement mass, independent of speed and working depth. Draft in a medium textured soil is estimated to be about 80% and in a coarse textured soil, 53% of draft in a fine texture soil. Bowers (1989) reported that the ASAE Standard for disk harrow draft tended to underestimate measured draft for tandem disk harrows in the medium and coarse textured soils of North Carolina.

Disk harrow draft is described as a positive linear function of speed and depth (Kydd et al., 1984; Summers et al., 1986) but primary tillage draft has also been reported to be a quadratic function of speed (Krishnan et al., 1988) and depth (Grisso et al., 1994).

2.6.6 Disk Coulters

Most no-till planters and drills and many tillage implements use disk coulters to cut surface residue and in some cases to till a narrow band of soil. Draft data for coulters are currently not reported by ASAE. Based on soil bin tests in sandy loam and clay loam soils, coulter draft and vertical forces are lowest for thin coulters with small wedge slopes (Tice and Hendrick, 1992). Choi and Erbach (1986) noted that a 46 cm (18 in.) coulter has better residue cutting characteristics than a 41 cm (16 in.) coulter but residue cutting was more affected by soil strength than coulter shape. Draft and vertical forces are shown to increase with coulter depth and diameter (Choi and Erbach, 1986; Kushwaha et al., 1986), increase with soil strength (Choi and Erbach, 1986) and increase with the presence of crop residue on the soil surface (Kushwaha et al., 1986). Coulter shape had no effect on draft or vertical forces but forces tended to be higher for fluted than notched, ripple or smooth coulters (Choi and Erbach, 1986). Bowers (1985) cited work by Trouse and Reaves (1980) for various types of coulters in clay loam, silt loam and sandy loam soils where smooth coulter draft was lower (15% to 40%) than that for fluted and bubble coulters.

2.6.7 Field Cultivators

Field cultivators and combination tillage tools based on field cultivator design are among the most commonly used seedbed tillage implements. Draft data for field cultivators are published by ASAE (1993a) to be the same as that for a chisel plow. Field cultivator draft is described as linear with speed and quadratic with depth (ASAE, 1993a; Grisso et al., 1994).

2.6.8 Row Crop Cultivators

Row crop cultivators are designed for a wide range of soil and residue conditions. S-tine shanks stir and loosen soil over a wide area and are suitable for tilled fields with light or moderate residue (Springman et al., 1989). C-shanks slice and lift the soil, cutting weeds and pushing soil aside and thus are more suitable for harder soil and heavier residue. Conservation tillage (no-till) cultivators are heavy duty cultivators suitable for hard soils and heavy residue (Springman et al., 1989; Grisso and Schuler, 1992). Most no-till cultivators use a cutting coulter and a single 41 to 61 cm (16 to 24 in.) sweep to undercut weeds in the inter-row area. Some use cut-away disks to remove weeds adjacent to the row.

2.6.9 Row Crop Planters

Planting conditions in a conservation tillage system are not as uniform as in a conventionally tilled field with a prepared seedbed, but the planting objectives are the same: open a seed furrow, place the seed at the correct depth, cover and firm the soil over the seed. Most no-till planters use coulters to cut the residue and till a narrow band of soil. Removing or incorporating the residue from the soil surface allows faster soil warm-up and easier placement of fertilizer. When two or three coulters per row are run side-by-side, a zone of soil 15 to 30 cm (6 to 12 in.) wide is tilled, loosened and cleared of most surface residue.

Row crop planter draft are published in the current ASAE standard (1993a). The Standard assumes a prepared seedbed in a loam soil and includes motion resistance. Based on data reported by Frisby and Summers (1979), there appears to be little difference in draft across soil textural groups when planting in a firm, prepared seedbed. Bowers (1989) reported draft for seeding units only in a loamy sand to be similar to that reported by Stephens et al. (1981) in a silt loam soil. When planting with seed, fertilizer and herbicide application, planter draft tends to be higher and more variable. Chapin et al. (1988) noted a 75% increase in draft on a loamy sand when a fluted coulter was added to cut through crop residue but others have found little difference in planter draft between tilled and untilled soils (Stephens et al., 1981; Bowers, 1989). Apparently, added coulter draft was offset by lower rolling resistance in some situations. Measured drafts ranging from about 1200 to 1800 N/row are common with no consistent trends across soil textural groups (Bowers, 1989; Matthews et al., 1981; Reid et al., 1983; Stephens et al, 1981) even though a lower draft (500 to 1000 N/row) is reported for some soils (Bowers, 1989).

2.6.10 Grain Drills

Draft for conventional grain drills is reported in the current ASAE data (1993a). Draft includes motion resistance and the draft is independent of seeding depth and speed. Kydd et al. (1984) observed little difference in draft with furrow openers raised or lowered so draft was assumed to be largely a function of transport and press wheel rolling resistance. Grain drill draft does not appear to be affected by soil texture when seeding in a prepared seedbed (Frisby and Summers, 1979). Mungai (1991) reported conservation tillage drill draft to be about 80% of that in a conventionally tilled seedbed on loam soil and 75% of that on a sandy loam, presumably due to lower rolling resistance on firmer soil.

2.7 SOIL EROSION AND SURFACE RUNOFF

The effectiveness of conservation tillage systems is influenced by the amount of crop residue on the soil surface (Gilley et al., 1986). Even small amounts of crop residue reduce soil erosion (Mannering and Meyer, 1963; Meyer et al., 1970; Laflen et al., 1981; Dickey et al., 1984, 1985; Gilley et al., 1986). Corn or soybean residue covering 20% of the soil surface reduced soil loss by

50% compared to a bare surface (Dickey et al., 1984, 1985). As residue cover increased, runoff decreased (Gilley et al., 1986; Laflen et al., 1981), runoff velocity decreased (Gilley et al., 1986, Meyer et al, 1970) and sediment concentration in the runoff decreased (Mannering and Meyer, 1963; Laflen et al., 1981; Dickey et al., 1984; Gilley et al., 1986). Total soil loss (Laflen et al, 1981; Gilley et al., 1986) and the rate of soil loss (Gilley et al., 1986) also decreased as residue cover increased.

Soil erosion is also influenced by soil disturbance and field slope. As tillage and soil disturbance decrease, soil loss tends to decrease. For a given tillage system, soil loss increases with field slope (Dickey et al., 1985). Laflen et al. (1981) reported that there was no critical slope length beyond which crop residue was no longer effective in reducing erosion, and for a given slope, as residue cover increased, runoff rate, runoff velocity, sediment concentration and soil loss rate decreased (Gilley et al., 1987). No-till systems are associated with the least erosion and the least cumulative runoff (Dickey et al., 1984).

Frozen soil is associated with increased runoff and erosion (Chanasyk and Woytowich, 1986). Ice decreases infiltration by blocking soil pores. Severe erosion occurs from saturated, unprotected soil when the surface is thawed while deeper soil is still frozen (Flerchinger and Saxton, 1989a; Edwards and Burney, 1989). Long duration, low intensity rainfall on frozen soil leads to soil erosion similar to a severe summer storm on dry soil (Rudra et al., 1986).

2.8 MANURE RUNOFF

Manure runoff is a potential source of pollution. Runoff can occur from animal holding, manure storage or land areas where manure is spread. The high biological oxygen demand created by animal wastes is detrimental to fish (Long and Painter, 1991), excess nutrients promote eutrophication of aquatic plants and pathogens contaminate fish and drinking water. Pollution can be minimized by using conservation tillage practices or buffer strips to prevent contaminated runoff from reaching surface waters. Doyle et al. (1975) reported that a 7.6 m (25 ft) forest buffer strip was effective in preventing stream pollution from animal wastes. Vegetative filter strips were found to reduce nutrients, solids and oxygen demanding materials by more than 80% on a concentration basis and more than 95% on a weight basis (Dickey and Vanderholm, 1980). A terraced pasture effectively removed nutrients and solids from dairy feedlot runoff in South Carolina (Livingston and Hegg, 1980).

Some researchers have recommended that manure not be spread on frozen ground (Minshall et al., 1970; Phillips et al., 1981). Late fall and winter spreading of manure on frozen ground has led to pollution of surface water. Nutrient loss from runoff increases in proportion to the length of time spread manure remains on frozen, tilled soil (Hensler et al., 1970) but the greatest losses follow heavy rain near the time of manure application (Hensler et al., 1970; Minshall et al., 1970). Freezing, thawing and raindrop impact contribute to fecal nitrogen loss (Steenhuis, 1975). Winter applications are thought to pose a greater pollution risk due to decreased infiltration rates and longer survival of fecal bacteria during the cool, damp winter months (Doyle et al., 1975).

The fate of the first meltwater after winter spreading greatly affects nutrient loss. When water infiltrates, losses are low but when the water runs off, losses are high (Steenhuis et al., 1981). The greatest nutrient losses in runoff water are expected where manure is spread on melting snow or frozen soil covered with ice (Steenhuis, 1981; Klausner et al., 1976). Surface applications of liquid manure on frozen soil led to greater nitrogen (N), phosphorus (P) and potassium (K) concentrations in runoff water than incorporated spring, fall or split spring-fall applications in Ontario, Canada (Phillips et al., 1981). Nutrient concentration in the runoff increased in proportion to the manure application rate. As much as 20% of N, 12% of P and 14% of K were lost from manure applied to tilled, frozen soil (Hensler et al., 1970; Minshall et al., 1970).

Michigan recommendations are to avoid manure application on frozen or snow covered soils if possible (MSU, 1990), but if winter applications are made, solid manure should only be applied on slopes of 6% or less and liquid manures on slopes of 3% or less. Erosion and runoff control measures such as conservation tillage and vegetative buffer strips should separate manure treated areas from surface water.

2.9 PREDICTING CROP RESIDUE COVER

Crop residue cover (%) increases with residue mass and residue mass is correlated with grain yield at harvest. Corn, winter wheat and oats produce about 1 kg (2.2 lb), 1.7 kg (3.7 lb) and 2 kg (4.4 lb), respectively, of crop residue per kg of grain produced (Robertson and Mokma, 1978; USDA-SCS, 1992). Residue cover increases with crop yield and regression data based on these relationships have been published (Gregory, 1982; Dickey et al., 1984; Gilley et al., 1986; Smith et al., 1987). Greb (1967) estimated that 3,600 kg/ha (3,200 lb/ac) of flat, uniformly distributed wheat residue was needed for 100% soil cover but more was needed under field conditions. More than 3,600 kg/ha (8,000 lbs/ac) of corn residue was needed for 100% cover (Gregory, 1982; Dickey et al., 1984; Smith et al., 1987). High-yielding corn typically left 90%-95% cover and small grains and lower yielding corn left 70%-85% cover (Shelton et al., 1992b).

Crop residue decays and is lost over time. The rate of residue decomposition is a function of time, temperature, moisture and the initial carbon:nitrogen ratio (Ghidey et al., 1985). Smith et al. (1987) reported corn residue lost over winter in Nebraska in the range of 10-15%. Ghidey et al. (1985) reported a 71% loss of corn residue over 10 months in Missouri.

2.10 TILLAGE EFFECTS ON CROP RESIDUE

There is an interaction of residue and tillage implement on the amount of residue cover left after tillage. Soybean and dry bean residue are fragile and much more likely to shatter and be buried during tillage than non-fragile residue such as corn, wheat, oats or hay (Shelton et al., 1992b). A single pass of a chisel plow with twisted points will leave 40-70% of non-fragile residue on the soil surface but only 10-30% of a fragile residue. Colvin et al. (1986) reported residue changes during tillage ranging from 80% disappearance of soybean residue following a single pass of a chisel plow to an increase due to uncovering of buried residue by a no-till planter. Shelton et al. (1992b) listed expected reductions in residue cover for each pass of several tillage implements.

2.11 CROP RESIDUE EFFECT ON SOIL WATER EVAPORATION

Water is removed from the soil profile through drainage, plant use and evaporation. Early in the spring and after harvest when a crop is not growing, evaporation is required to remove soil moisture to a level below field capacity and suitable for tillage. Evaporation is largely influenced by solar radiation, temperature, wind and the interaction of temperature and wind (Brun et al., 1986). Since crop residue reflects solar radiation and reduces both wind velocity and temperature at the soil surface, the rate of soil water evaporation is reduced by residue cover (Bond and Willis, 1969; 1970; Smika, 1983; Brun et al., 1986; Aase and Tanaka, 1987).

Evaporation occurs in three stages (Bond and Willis, 1969; 1970). During the first stage, the rate of water loss is high, similar to a free water surface and controlled primarily by external conditions. Much of the total water loss occurs during the first (constant rate) stage. The second stage begins when dry soil appears. The hydraulic properties of the soil begin to regulate drying so the drying rate decreases rapidly. During the third stage, evaporation is almost entirely by vapor diffusion; the drying rate is slow and relatively constant. Crop residue cover has the greatest effect during Stage 1 when the soil surface is wet (Bond and Willis, 1969). Bond and Willis (1969) measured a nearly linear reduction in Stage 1 drying as residue cover approached 100%.

Cumulative evaporation has been shown to be related to both precipitation frequency and amount. When rains were infrequent and light and evaporation continued for an extended time, there was little difference in cumulative evaporation between bare or residue covered surfaces (Bond and Willis, 1969; Brun et al., 1986; Aase and Tanaka, 1987). But as rainfall increased in frequency and amount, there was less cumulative evaporation from a stubble covered than a bare soil (Brun et al., 1986).

2.12 TILLAGE AND RESIDUE EFFECT ON CROP YIELD

Corn grown in a no-till system may yield less than corn grown in more conventional tillage systems (Griffith et al., 1973; Erbach, 1982; Griffith et al., 1992). No-till corn grain yields tend to be lower on fine textured, poorly drained soils than on medium or coarse textured soils (Griffith et al., 1992). The lower yields are attributed to low soil temperatures early in the growing season due to crop residue cover (Allmaras et al., 1964; Kaspar et al., 1987; Kaspar et al., 1990; Swan et al., 1987; Al-Darby and Lowery, 1987).

Crop residue may also have allelopathic effects when corn follows corn in a rotation. Aqueous extracts of corn residue were shown to reduce corn seedling growth under laboratory conditions (Yakle and Cruse, 1983; 1984). Deep or primary tillage did not seem to affect corn emergence as much as the amount of surface residue (Erbach et al., 1992; Erbach and Kaspar, 1993). Shinners and Wang (1992) reported that a 20-30 cm (8-12 in) residue free band appeared optimal with respect to early season soil warm-up and crop emergence.

2.13 SOIL COMPACTION

Badger (1972) noted that producers valued manure as a soil amendment but noted several drawbacks from using manure including soil compaction. Soil compaction is the reduction of pore space from the compression of the soil. An ideal soil has about 50% of its total volume as pore space (Robertson and Erickson, 1980). Compact soil layers have inadequate pore space for drainage, aeration and root growth. Soil compaction can delay emergence of corn plants, reduce plant height and grain yields and increase grain moisture at harvest (Erbach et al., 1988; Voorhees et al., 1989). In the short-term, soil compaction can be alleviated by tillage (Cooper, 1971). In the long-term, natural phenomena such as wetting and drying and freezing and thawing also reduce soil compaction (Larson and Allmaras, 1971). Deep soil compaction can persist for at least four years despite annual freezing and thawing (Voorhees et al., 1986; Lowery and Schuler, 1991).

Some Michigan soils have naturally compact soil layers (Johnson et al., 1986) but most soil compaction is caused by heavy vehicle traffic. Tillage or vehicle induced soil compaction was greater in wet than dry soils (Voorhees et al., 1986; Voorhees et al., 1989; Robertson and Erickson, 1980). Most tire sinkage (70-90%) occurs on the first wheel pass (Guo and Schuler, 1992; Taylor et al., 1982) as does the greatest increase in soil density (70%; Taylor et al., 1982). Repetitive traffic leads to excessive deep compaction under both moderate (3.8 t; Petelkau and Dannowski, 1990) and heavy (13.8 t; Wood et al., 1993) axle loads. Finer textured (clay) soils are more susceptible to soil compaction than medium textured (loam) soils (Gameda et al., 1985; Lowery and Schuler, 1991).

There appears to be an interaction of weather and deep compaction on grain yield. A small amount of compaction tends to increase yield in years when soil moisture is short and decrease in years when the soil is wet (Wolf et al., 1981; Gameda et al., 1985; Voorhees et al., 1989; Voorhees, 1990; Johnson et al., 1990; Bicki and Siemens, 1990). Soil compaction has a greater impact on poorly drained than well drained soils (Voorhees et al., 1986). Gruber and Tebrügge (1990) reported that the danger of subsoil compaction is less with reduced tillage systems. Less tilled soils are reported to be more resistant to vehicle traffic and exhibit less tire sinkage and pore volume change as well as lower measured soil stress beneath the wheel load. Robertson et al. (1979) reported improved crop yields when compact soil layers below the plow layer were broken, but only if the soil was relatively dry at the time of tillage.

2.14 EFFECT OF MANURE ON SOIL PHYSICAL PROPERTIES

Several researchers have reported beneficial effects of manure on soil physical properties. Manure application can improve aggregate stability (Elson; 1941, 1943), increase soil water holding capacity and decrease soil water evaporation (Unger and Stewart, 1974). Manure is reported to increase soil organic matter, decrease soil bulk density (Mathers and Stewart, 1980; Sommerfeldt and Chang, 1985) and increase hydraulic conductivity (Mathers and Stewart, 1980). The addition of organic matter from manure can improve water infiltration (Mazurak et al., 1955; Minshall, 1969; Swader and Stewart, 1972; Converse et al., 1976; Mathers et al., 1977) and increase soil moisture in the plow layer (Wilkins and Rasmussen, 1993). Lower tillage tool draft requirements are reported in manure applied soils (Sommerfeldt and Chang, 1985; Wilkins and Rasmussen, 1993).

2.15 SUITABLE DAYS FOR FIELDWORK

Machinery selection for field work is influenced by many factors. Labor hours available, number of operations carried out and crop acreage are among the most important (Edwards and Boehlje, 1980). Soil type and crop and weather parameters are also important (Rotz and Black, 1985). Important crop parameters include penalties (costs) for crop loss due to untimely field operations. These timeliness penalties are generally the result of adverse weather limiting the number of days suitable for fieldwork or, under more normal conditions, selecting a machinery set too small to complete the fieldwork in a timely fashion. A machinery complement capable of completing the required operations within a specified time in 8 years out of 10 generally provides the best basis for selection (Elliott et al., 1977; Rotz et al., 1983; Rotz and Black, 1985).

2.15.1 Suitable Days

Suitable working days are the days available in a scheduled period during which field operations can be performed (Von Bargen et al., 1986). The number of suitable days in a time period is influenced by climatic region, soil slope and texture, drainage, operation to be performed and traction and flotation devices (ASAE, 1993a). Field operations that delay the timely planting of corn increase the risk of economic loss for both crop and livestock producers. Early planting of corn is important whether harvested for silage or grain. In southern Michigan there was an average grain loss of 63 kg/ha (1 bu/ac) for each day of delay past the recommended May 1-10 planting period (Erdmann and Hildebrand, 1977). Early planted corn produced higher yielding, higher quality corn silage. Compared to corn planted May 9, total silage yield decreased 7% and 9% for corn planted May 22 and June 2, respectively. Silage quality declined as the grain content fell from 54% to 43% with the late planting.

A common strategy for manure land application is to spread stored manure and till the soil in the spring prior to planting and in the fall after corn harvest. Since timeliness penalties for corn planting begin to accumulate in early May and soil conditions for tillage and spreading deteriorate rapidly in the fall, selecting machinery capable of completing field operations within the time available is particularly important.

2.15.2 Prediction of Suitable Days

Estimates of suitable days for fieldwork have been derived from historic records of crop and field conditions (Fulton et al, 1976). This data is useful in the geographic area where collected but it is not transferable to other areas and new data is difficult to acquire. Records over several years are needed to estimate the probability of suitable conditions over a period of days (Selerio and Brown, 1972). An alternative method to predict suitable days is computer simulation. Models have been developed that impose soil trafficability criteria on a soil moisture balance. Models that included precipitation, runoff, evapotranspiration and drainage showed good results when compared to validation sources (Selerio and Brown, 1972; Dyer and Baier, 1979; Acharya et al., 1983). Crop residue effects were added to some models (Elliott et al., 1977; Von Bargen et al., 1986) while others included the possibility of snow cover or frozen soil (Rutledge and McHardy, 1968; Baier, 1973; Tulu et al., 1974; Rosenberg et al., 1982; McGechan and Cooper, 1994) or rainfall on the day of scheduled field operations (Elliott et al., 1977; Rosenberg et al., 1982; Acharya et al., 1983).

Soil texture and drainage affect water holding capacity and water movement through the soil and are important factors influencing the number of days available for field operations (Elliott et al, 1977; Rosenberg et al, 1982). In southern Michigan, sandy soils were estimated to provide about 15% more suitable days than clay soils (Rosenberg et al., 1982). In Indiana, coarse textured soils allowed about 10% more and fine textured soils about 15% less suitable days than a medium textured soil (Parsons and Doster, 1980). In southern Ontario, about 15% more time was expected on sandy than clay loam soils (ASAE, 1993b).

Since crop residue reflects solar radiation and reduces both wind velocity and temperature at the soil surface, the rate of soil water evaporation is reduced by residue cover (Bond and Willis, 1969, 1970; Smika, 1983; Brun et al., 1986; Aase and Tanaka, 1987). This shading of the soil reduces the number of days suitable for fieldwork. Residue cover has the greatest effect during Stage 1 evaporation when the soil surface is wet (Bond and Willis, 1969). Bond and Willis (1969) measured a nearly linear reduction in Stage 1 drying with increasing residue cover until the soil was completely covered. Increasing residue beyond 100% cover continued to reduce drying but at a diminished rate. Cumulative evaporation from soil cores fully shaded by wheat residue was about 40% of that from a bare soil surface during the first 3 to 4 days of Stage 1 drying (Bond and Willis, 1969). The straw was clean, bright and uniformly distributed and probably reflected solar radiation more effectively than could be expected of weathered residue. The evaporation potential of shaded columns ranged from about 40% to 60% of unshaded soil columns (Bond and Willis, 1970) and Stage 1 evaporation of soil covered with 4,600 kg/ha (4,100 lb/ac) of wheat residue was about 63% of that from bare soil (Aase and Tanaka, 1987). A less pronounced reduction in Stage 1 drying (80% of a bare surface) was reported by Brun et al. (1986) for a field covered with wheat residue.

3. MODEL DEVELOPMENT

DAFOSYM is a comprehensive computer model that simulates alfalfa and corn growth, harvest, storage, feeding, and use on a dairy farm (Rotz et al., 1989). Recently, submodels were added for manure production, collection, storage and application (Borton et al., 1995). To enable the simulation and evaluation of the interaction of manure storage, land application and tillage systems, submodels were added to predict suitable days under a range of soil and crop residue conditions, draft of a wide range of tillage and seeding implements and scheduling of tillage, planting and manure application.

3.1 DEVELOPMENT OF THE TILLAGE DRAFT MODEL

The draft force required to pull a tillage or seeding implement is primarily a function of the width of the implement and the speed at which it is pulled. Tillage draft is influenced by site specific conditions including soil type, moisture, density and residue cover (Michel et al., 1985). Draft also depends upon operating depth (Summers et al., 1986; Khalilian et al., 1988; Grisso et al., 1994) and geometry of the tillage tool (Upadyaya et al., 1984). Wide variations in draft are common both within and between soil textural groups (Bowers et al., 1989). Equations have been developed for specific implements such as the moldboard plow (Oskoui and Witney, 1982; Oskoui et al., 1982) which relates draft to site specific conditions, but valid results require detailed information about soil conditions. Dafosym requires a general model which provides reasonable values for most conditions without knowledge of specific soil conditions.

Available information on draft requirements for tillage and seeding equipment was reviewed. Draft was defined as the force required to propel an implement in the direction of travel (ASAE, 1993e). Unless noted otherwise, draft required to overcome rolling resistance of the implement was included. The two major phases of this work were: 1) to develop a model with machine-specific parameters that predicts typical draft requirements for major tillage, planting and seeding implements and 2) to integrate this model in DAFOSYM for predicting tillage and planting power requirements.

3.1.1 General Draft Model

A simple function was used to model tillage draft under general conditions where draft is a function of soil texture, implement width, depth and speed of operation:

$$D = F_i * [\mathbf{A} + \mathbf{B}(S) + \mathbf{C}(S)^2] * W * TD$$

where

D is implement draft, kN (lbf).

F is a soil texture adjustment factor.

i is 1 for fine, 2 for medium and 3 for coarse textured soils.

A, **B** and **C** are machine specific parameters.

S is speed, km/h (mph).

W is machine width (m, ft), number of rows or tools.

TD is tillage depth (cm, in.) for major tillage tools, 1 (unitless) for minor tillage tools and seeding implements.

Although the same equation was used for all machines, only one or two of the parameters were used to describe the draft of any given machine.

A form of this model was previously used by Summers et al. (1986) for reporting moldboard plow, chisel plow, sweep plow and disk harrow draft. Compared to using several different equations, this simple equation with machine specific parameters has the advantage of being easily understood and convenient to use. Draft data can be estimated per unit of depth of operation for most major tillage tools. A description of tillage tools and components has been provided by Siemens et al. (1992) and can be found in the ASAE Standards (1993c, d, e).

Rather than using traditional soil textural classifications such as clay or loam, the proposed data categorize soil groups as fine, medium or coarse. Fine textured soils can be described as predominantly clay, medium textured are loamy soils and coarse textured are sandy soils. This method of grouping soils has been used by Rotz and Black (1985) and to a limited extent by others (Hunt, 1977; White, 1977). This form of classification is currently being used by some tillage implement and herbicide application equipment manufacturers.

A major part of the model development was to determine the machine specific parameters **A**, **B** and **C**. Each term is a function of tillage tool geometry.

In addition, the constant term **A** is a function of soil strength while the coefficient of speed terms (**B** or **C**) are related to soil bulk density. Soil strength was assumed to decline and bulk density to increase from fine to coarse textured soils.

The primary source for new draft data was published research. In some cases, the machine parameters were published for specific conditions and, based on a comparison of reported data across soil textural groups, extrapolated to a wider range of conditions. If parameter estimates were not previously published, the draft/speed relationship was estimated from published data of similar tools and the ratio of the coefficient of speed (**B** or **C**) to the constant (**A**) was maintained. Data selected were not necessarily means of available data but values which seemed most reasonable for typical conditions.

3.1.2 Subsoilers

Reported draft for a conventional subsoiler shank varies widely, ranging from 90 N/t/cm (51 lb/t/in., Wolf et al., 1981) to 675 N/t/cm (385 lb/t/in., Wildman et al., 1978). Based on a comparison of reported draft across soil textural groups, subsoiler draft in medium and coarse textured soils is estimated as 70% and 45%, respectively of that for fine textured soils (Bowers, 1989; Cooper, 1971; Godwin et al., 1985; Khalilian et al., 1988; Mielke et al., 1992; Reeder et al., 1992; Shinners, 1989; Smith and Williford, 1988; Smith, 1989; Spoor and Godwin, 1978; Trouse and Reaves, 1980; Wildman et al., 1978;

Table 3.1 Draft parameters for tillage and seeding implements.

Implement	SI units	Parameters, SI A	B	C	English units	Parameters, English A	B	C	Soil Factor F_1	F_2	F_3	Range ±%
MAJOR TILLAGE TOOLS												
Subsoiler/Manure Injector												
narrow point	N/t/cm	226	---	1.81	lbf/t/in.	129	---	2.71	1.0	0.70	0.45	50
30 cm winged point	N/t/cm	294	---	2.35	lbf/t/in.	167	---	3.52	1.0	0.70	0.45	50
Moldboard Plow	N/cm²	6.5	---	0.051	lbf/in.²	9.4	---	0.191	1.0	0.70	0.45	40
Chisel Plow												
5 cm straight point	N/t/cm	91	5.39	---	lbf/t/in.	52	4.94	---	1.0	0.85	0.65	50
7.5 cm shovel or 30 cm sweep	N/t/cm	107	6.34	---	lbf/t/in.	61	5.81	---	1.0	0.85	0.65	50
10 cm concave shovel	N/t/cm	123	7.29	---	lbf/t/in.	70	6.68	---	1.0	0.85	0.65	50
Sweep Plow												
primary tillage	N/cm²	3.9	0.19	---	lbf/in²	5.7	0.44	---	1.0	0.85	0.65	45
secondary tillage	N/cm²	3.1	0.15	---	lbf/in²	4.5	0.35	---	1.0	0.85	0.65	35
Disk Harrow, Tandem												
primary tillage	N/cm²	3.09	0.16	---	lbf/in.²	4.5	0.37	---	1.0	0.88	0.78	50
secondary tillage	N/cm²	2.16	0.11	---	lbf/in.²	3.1	0.26	---	1.0	0.88	0.78	30
Disk Harrow, Offset												
primary tillage	N/cm²	3.64	0.19	---	lbf/in.²	5.3	0.44	---	1.0	0.88	0.78	50
secondary tillage	N/cm²	2.54	0.13	---	lbf/in.²	3.7	0.30	---	1.0	0.88	0.78	30
Disk Gang, Single												
primary tillage	N/cm²	1.24	0.06	---	lbf/in.²	1.8	0.14	---	1.0	0.88	0.78	25
secondary tillage	N/cm²	0.9	0.04	---	lbf/in.²	1.2	0.09	---	1.0	0.88	0.78	20
Disk Coulters												
smooth or ripple	N/t/cm	55	2.73	---	lbf/t/in.	31	2.50	---	1.0	0.88	0.78	25
bubble or flute	N/t/cm	66	3.28	---	lbf/t/in.	37	3.00	---	1.0	0.88	0.78	25
Field Cultivator												
primary tillage	N/t/cm	46.0	2.77	---	lbf/t/in.	26.0	2.54	---	1.0	0.85	0.65	30
secondary tillage	N/t/cm	32.0	1.94	---	lbf/t/in.	19.0	1.78	---	1.0	0.85	0.65	25
Row Crop Cultivator												
S-tine	N/row/cm	140	7.00	---	lbf/r/in.	80.0	6.41	---	---	---	---	15
C-Shank	N/row/cm	260	13.00	---	lbf/r/in.	148	11.91	---	---	---	---	15
No-Till	N/row/cm	435	21.75	---	lbf/r/in.	248	19.92	---	---	---	---	20
Rod Weeder	N/m/cm	210	10.70	---	lbf/ft/in.	37.0	3.02	---	1.0	0.85	0.65	25
Disk-Bedder	N/r/cm	185	9.50	---	lbf/r/in.	106	8.70	---	1.0	0.88	0.78	40

Table 3.1 (cont'd)

Implement	SI units	Parameters, SI A	B	C	English units	Parameters, English A	B	C	Soil Factor F_1	F_2	F_3	Range ±%
MINOR TILLAGE TOOLS												
Rotary Hoe	N/m	600	---	---	lbf/ft	41	---	---	1.0	1.0	1.0	30
Coil Tine Harrow	N/m	250	---	---	lbf/ft	17	---	---	1.0	1.0	1.0	20
Spike Tooth Harrow	N/m	600	---	---	lbf/ft	40	---	---	1.0	1.0	1.0	30
Spring Tooth Harrow	N/m	2,000	---	---	lbf/ft	135	---	---	1.0	1.0	1.0	35
Roller Packer	N/m	600	---	---	lbf/ft	40	---	---	1.0	1.0	1.0	50
Roller Harrow	N/m	2,600	---	---	lbf/ft	180	---	---	1.0	1.0	1.0	50
Land Plane	N/m	8,000	---	---	lbf/ft	550	---	---	1.0	1.0	1.0	45
SEEDING IMPLEMENTS												
Row Crop Planter, prepared seedbed												
mounted-seeding only	N/row	500	---	---	lbf/r	110	---	---	1.0	1.0	1.0	25
drawn-seeding only	N/row	900	---	---	lbf/r	200	---	---	1.0	1.0	1.0	25
drawn-seed, fert. and herb.	N/row	1,550	---	---	lbf/r	350	---	---	1.0	1.0	1.0	25
Row Crop Planter, No-Till												
seed, fert. and herb, 1 fluted coulter/row	N/row	1,820	---	---	lbf/r	410	---	---	1.0	0.96	0.92	25
Row Crop Planter, Zone-Till												
seed, fert. and herb.	N/row	3,400	---	---	lbf/r	765	---	---	1.0	0.94	0.82	35
Grain Drill w/press wheels												
<2.4 m drill width	N/row	400	---	---	lbf/r	90	---	---	1.0	1.0	1.0	25
2.4 to 3.7 m drill width	N/row	300	---	---	lbf/r	67	---	---	1.0	1.0	1.0	25
>3.7 m drill width	N/row	200	---	---	lbf/r	25	---	---	1.0	1.0	1.0	25
Grain Drill, No-Till												
1 fluted coulter/row	N/row	720	---	---	lbf/r	160	---	---	1.0	0.92	0.79	35
Hoe Drill												
primary tillage	N/m	6,100	---	---	lbf/ft	420	---	---	1.0	1.0	1.0	50
secondary tillage	N/m	2,900	---	---	lbf/ft	200	---	---	1.0	1.0	1.0	50
Pneumatic Drill	N/m	3,700	---	---	lbf/ft	250	---	---	1.0	1.0	1.0	50

Williams et al., 1979; Wolf et al., 1981). Draft is linearly related to depth and quadratic with respect to speed (Table 3.1). At 6.4 km/h (4 mph), the proposed draft ranges from about 135 to 300 N/t/cm, similar to current ASAE data which ranges from about 150 to 315 N/t/cm. Draft for a subsoiler with 30 cm (12 in.) winged points is estimated as that for a narrow point increased by 30% (Spoor and Godwin, 1985).

3.1.3 Liquid Manure Injectors

The proposed liquid manure injector draft data do not include tanker rolling resistance. Similar to subsoiler draft, the proposed data (Table 3.1) are a positive linear function of depth and quadratic with speed. Draft in medium and coarse textured soils is estimated as 70% and 45%, respectively, of that for fine textured soils. The proposed data for injector draft in a fine textured soil are similar to that reported by Godwin et al. (1985) and Negi et al. (1978) for winged injectors in clay loam and Laguë (1991) in firm clay soils. Based on the proposed data, injector draft ranges from 200 N/t/cm in a coarse textured soil to 450 N/t/cm in a fine textured soil (Table 3.1).

3.1.4 Moldboard Plows

Since most reported plow draft data are in reasonable agreement with the current ASAE data (Bowers, 1985; Bowers, 1989; Chaplin et al., 1986; Frisby and Summers, 1979; Nichols et al., 1958; Reaves and Schafer, 1975; Reid, 1978; Reid, 1983; Self et al., 1983; Stephens et al., 1981; Summers et al., 1986;

Wilkins and Rasmussen, 1993; Williams et al., 1979; Zwilling and Hummel, 1988), the proposed parameters (Table 3.1) are based on the ASAE data. Draft is linear with respect to depth, quadratic with speed (ASAE, 1993a; Summers et al., 1986) and adjusted for soil texture. Draft for medium and coarse textured soils is estimated as 70% and 45%, respectively, of that for fine textured soils. Bowers (1989) reported that moldboard plow draft in the sandy loam soils of North Carolina tended to be underestimated by the ASAE Standard. With the proposed model, predicted draft for coarse textured soils is somewhat higher than that reported by ASAE for sand and sandy loam soils.

3.1.5 Chisel Plows

The proposed parameters for chisel plow draft (Table 3.1) are based on a comparison of reported values across soil textural groups (Bowers, 1989; Frisby and Summers, 1979; Hendrick, 1980; Hunt, 1983; Reid, 1978; Reid, 1983; Self et al., 1983; Stephens et al., 1981; Summers et al., 1986; Zwilling and Hummel, 1988; Grisso et al., 1994). Draft is generally found to be a linear function of both depth and speed (Summers et al., 1986; Kydd et al., 1984; Gregory and M'Hedhbi, 1988) but draft has also been reported to be a quadratic function of depth (Grisso et al., 1994). Draft factors **A** and **B** for medium textured soil are based on data reported by Summers et al. (1986) for silt loam soil. Draft in medium and coarse textured soils is estimated as 85% and 65%, respectively, of the draft in fine textured soil. Bowers (1989) reported that the ASAE Standard data tended to over-estimate draft for chisel plows in the medium and coarse textured soils of North Carolina. Chisel plow draft based on the proposed parameters tends to be lower than that reported in the current ASAE Standard.

3.1.6. Sweep Plows

Sweep plows are used to loosen soil and undercut weeds while leaving the soil surface undisturbed. The current ASAE Standard does not include draft data for sweep plows, but sweep plows and similar tillage tools will likely come into wider use as conservation tillage systems gain wider acceptance.

Summers et al. (1986) measured speed-draft relationships of sweep plows in clay loam and silt loam soils in Oklahoma. Kydd et al. (1984) reported draft data for sweep plows (blade cultivators) in both primary and secondary tillage conditions. Draft was reported to be linear with respect to speed and depth (Summers et al., 1986; Kydd et al., 1984). Comparisons of sweep plow draft across soil textural groups were not found. The proposed sweep plow parameters are based upon a composite of reported data (Summers et al., 1986; Kydd et al., 1984). Similar to chisel plows, field cultivators and other chisel-type tools, draft in medium and coarse textured soils is estimated to be 85% and 65%, respectively, of that in a fine textured soil (Table 3.1). Based on sweep plow draft data reported by Kydd et al. (1984), draft during secondary tillage is estimated as 70% of that required for primary tillage.

3.1.7 Disk Harrows

Summers et al. (1986) reported greater draft for an offset compared to a tandem disk, but direct comparisons were difficult due to greatly different soil conditions. Bowers (1989) reported tandem disk draft about 69% and 89%, respectively, of that for an offset disk on fine sandy loam and sandy loam soils. A composite of values reported for silt loam soils (Bowers, 1989; Frisby and Summers, 1979; Self et al., 1983) indicates tandem disk draft to be about 90% of that for an offset disk. In the proposed parameters, draft of a tandem disk is estimated to be 85% of that required for an offset disk at the same depth.

Disk draft is typically greater during primary than secondary tillage. However, farmers generally perceive greater draft during secondary tillage due to increased operating depth and reduced tractive efficiency in tilled soil. Draft for a tandem disk during secondary tillage was about 38% of primary tillage in a loamy fine sand (Self et al., 1983), 73% in a loamy sand, 73% in a fine sandy loam, 76% in a sandy loam and 56% in a loam (Bowers, 1989). Offset disk draft for secondary tillage was about 63% of primary tillage draft in a clay loam (Reid, 1978), 58% in a sandy clay loam and 93% in a sandy loam (Reid et al., 1983). In the proposed parameters, draft during secondary tillage is assumed to be 70% of that required for primary tillage.

Since most newer tandem and offset disks can limit depth of tillage with transport wheels, draft data based on depth of tillage are preferred to draft estimates based on mass alone. The proposed data for primary tillage with a tandem disk harrow in fine textured soils are based on data presented by Summers et al. (1986) and a comparison of reported draft across soil textural groups (Bowers, 1989; Frisby and Summers, 1979; Kydd et al., 1984; Reid, 1978; Reid et al., 1983; Self et al., 1983; Stephens et al., 1981; Williams et al., 1979; Zwilling and Hummel, 1988; Grisso et al., 1994). Draft (N/cm^2) for medium and coarse textured soils is estimated as 88% and 78%, respectively, of draft for a fine textured soil.

Since ASAE disk harrow draft data do not consider depth, a direct comparison with the proposed data is difficult. The proposed data predict a narrower range of draft at a given depth than the current Standard. However, in a medium textured soil the proposed data are similar to ASAE data (55 kg/blade) for a silt loam soil at depths of 14 cm (5.5 in.) and 20 cm (8 in.), respectively, for primary and secondary tillage with a tandem disk harrow at 8.9 km/h (5.5 mph). The proposed draft for an offset disk is similar to ASAE data (105 kg/blade) at a depth of 18 cm (7 in.) during primary tillage and 23 cm (9 in.) during secondary tillage.

3.1.8 Single Disk Gangs

Single disk gangs are frequently used on combination tillage tools for both primary and secondary tillage. Draft data for single disk gangs are currently not reported by ASAE. Hunt (1977) reported typical draft for a single disk gang as about 50% of that for a light tandem disk. But the gang angle is typically less for a single disk gang (8° to 12°) than a tandem disk harrow (18° to 22°) and reducing the gang angle tends to reduce both depth of operation and draft (Sommer et al., 1983). Based on draft-gang angle relationships described by Sommer et al. (1983), reducing the gang angle from 20° to 10° will reduce draft by 25 to 30%. In the proposed parameters, draft for a single disk gang at a 10° gang angle is estimated as 40% of that for a tandem disk under similar conditions (Table 3.1).

3.1.9 Disk Coulters

Coulter draft in the range of 45 to 50 N/cm of depth for a 46 cm (18 in.) rippled coulter was reported by Choi and Erbach (1986) based on soil bin tests in a silty-clay-loam and cornstalk residue. In soil bin tests in a clay loam soil and straw residue, Kushwaha et al. (1986) measured draft in the range of 35 to 40 N/cm of depth for a smooth coulter, 46 cm (18 in.) in diameter. In general, draft reported by Trouse and Reaves (1980) tended to be higher than that reported by Choi and Erbach (1986) or Kushwaha et al. (1986), ranging from about 60 N/cm for a smooth coulter in a sandy loam to 125 N/cm for a bubble coulter in clay loam soil.

The proposed draft parameters for smooth and ripple coulters (Table 3.1) were established from a composite of reported data (Choi and Erbach, 1986; Kushwaha et al., 1986; Trouse and Reaves, 1980). Coulter draft is assumed to be a linear function of both depth and speed with a 20% increase for fluted and bubble coulters. Similar to disk harrows, draft in medium and coarse textured soils is 88% and 78%, respectively, of the draft in fine textured soils.

3.1.10 Field Cultivators

The proposed parameters for field cultivator draft (Table 3.1) are based on a summary of reported draft data (Dumas and Renoll, 1982; Frisby and Summers, 1979; Stephens et al., 1981; Kydd et al., 1984; Zwilling and Hummel, 1988; Grisso et al., 1994). Few data are available comparing draft across soil textural groups so similar to chisel plows, draft for medium and coarse textured soils was estimated as 85% and 65%, respectively, of the draft in a fine textured soil. Based on the draft data reported by Kydd et al. (1984), draft during secondary tillage was estimated as 70% of that required for primary tillage. Field cultivator draft (N/t/cm) based on the proposed parameters tends to be lower during secondary tillage (30-50 N/t/cm) and higher during primary tillage (45-70 N/t/cm) than that based on the current ASAE Standard data (45-55 N/t/cm).

3.1.11 Row Crop Cultivators

Row crop cultivator draft (N/m of width) is reported as linear with respect to depth (ASAE, 1993a). Hunt (1977) reported a range of values similar to that reported by ASAE. Frisby and Summers (1979) reported cultivator draft in clay, loam and sand soils. Stephens et al. (1981) reported draft for row cultivators with 3 to 5 sweeps or 5 S-tine shanks per row in a sandy-loam soil. No draft data for conservation tillage cultivators were found.

The proposed parameters for S-tine and C-shank cultivators (Table 3.1) are based on reported draft data (ASAE, 1993a; Hunt, 1977; Frisby and Summers, 1979; Stephens et al., 1981). The data (N/cm/row) for no-till cultivators (Table 3.1) are estimated from proposed sweep plow data (assuming a 22 in., 56 cm sweep) plus added draft for three coulters to approximate the draft of one cutting coulter and two cut-away disks per row. Draft was assumed to be a linear function of both speed and depth. Similar to a chisel plow, field cultivator and sweep plow draft, draft in medium and coarse textured soils is assumed as 85% and 65%, respectively, of draft in a fine textured soil. Based on the proposed data, draft for the S-tine cultivator is at the low end and the C-shank cultivator with sweeps at the high end of the range currently reported by ASAE.

3.1.12 Rotary Hoes

Rotary hoes were designed to dislodge small weeds and loosen crusted soil early in the growing season (Springman et al., 1989). Rotary hoes work best at relatively high speeds in tilled fields with light to moderate residue cover. Rotary hoe draft is reported to be linear with respect to speed (ASAE, 1993a). A range of expected draft (N/m of width) was reported by Hunt (1977). Rotary hoe draft reported by Stephens et al. (1981) was lower than that predicted by the current ASAE data. Based on Stephens et al. (1981), the proposed data for rotary hoe draft are 500 N/m, independent of travel speed. A single value with an expected range or variation is consistent with data reported for other minor tillage tools (Table 3.1).

3.1.13 Rod Weeders

Rod weeders use a rotating round or square rod running below the soil surface to undercut weeds and leave them lying on the soil surface. A range of expected draft was reported by ASAE (ASAE, 1993a) and a similar range was reported by Hunt (1977). Kydd et al. (1984) reported draft data for rod weeders under typical Canadian prairie conditions and indicated draft to be linear with respect to speed. The proposed parameters for rod weeder draft in medium textured soil are based on Kydd et al. (1984). Draft is adjusted for soil texture similar to other cultivation tools with medium and coarse textured soils causing 85% and 65%, respectively, of the draft in fine textured soils (Table 3.1).

3.1.14 Minor Tillage Tools

ASAE spike harrow data (440-730 N/m) are similar to that reported by PAMI (PAMI, 1986); therefore a single value (590 N/m) with an expected range of variation is provided. A similar modification was made for roller-packer (660 N/m), land plane (8,000 N/m) and spring tooth harrow (1,800 N/m) data. The proposed roller-harrow parameter (2,700 N/m) is a composite of the current ASAE roller packer data and the proposed field cultivator parameters. Proposed coil-tine harrow data (250 N/m) were derived from harrow-packer draft data

(PAMI, 1988). Disk-bedder draft (N/r/cm) are based on Reid (1978) and adjusted for soil texture similar to disk harrows.

3.1.15 Row Crop Planters

Row crop planter draft (N/row) is published in the current ASAE standard (ASAE, 1993a). The Standard data assumes a prepared seedbed in a loam soil and includes rolling resistance. Based on data reported by Frisby and Summers (1979), there appears to be little difference in draft across soil textural groups when planting in a firm, prepared seedbed. Bowers (1989) reported draft for seeding units only in a loamy sand to be similar to that reported by Stephens et al.(1981) in a silt loam soil. When planting with seed, fertilizer and herbicide application, planter draft tends to be higher and more variable. Measured drafts ranging from about 1,200 to 1,800 N/row are common with no consistent trends across soil textural groups (Bowers, 1989; Matthews et al., 1981; Reid et al., 1983; Stephens et al., 1981) even though a lower draft (500 to 1,000 N/row) is reported for some soils (Bowers, 1989).

Rolling resistance of transport and press wheels is a large portion of row planter draft. Row planter draft only increased about 10% when planting at 7.5 cm (3 in.) compared to 2.5 cm (1 in.) in a prepared seedbed of silt loam soil (Stephens et al., 1981) indicating little contribution to draft from the seeding units. Bowers (1989) indicated 15 to 20% lower draft in an untilled fine sandy loam soil compared to the same planter in a prepared seedbed, possibly due to lower rolling resistance on firm soil.

Since planter draft in a prepared seedbed does not appear to be greatly affected by soil texture or planting depth, row planter draft is estimated as 500 N/row for a mounted planter with seed units only (Table 3.1), 900 N/row for a drawn planter running only seeding units and 1,550 N/row when running seed, fertilizer and herbicide units in a prepared seedbed. Motion resistance was assumed to be less with no-till planters. No-till planter draft was estimated as 1,325 N/row with seed, fertilizer, herbicide units plus the estimated draft of one fluted coulter (320 to 470 N/row). Draft for zone-till planters was estimated as row unit draft (1,325 N/row) plus the draft of three fluted coulters per row (1,440 to 2,100 N/row).

The proposed row planter draft parameter (N/row) for a mounted planter with seed units only is at the lower end of the range listed in the current ASAE data (Table 3.1). Draft for a drawn planter with seed units only is somewhat higher than the upper end of the range listed by ASAE. The proposed data for row planters applying seed, fertilizer and herbicide are in the mid-range of that listed by ASAE.

3.1.16 Grain Drills

Since grain drill draft is not greatly affected by soil texture or seeding depth, but is greatly affected by rolling resistance, a range of draft (N/row) values based on drill width is proposed. Based on a synopses of reported data (Frisby and Summers, 1979; Mungai, 1991; Stephens et al., 1981; Kydd et al., 1984) draft data for a conventional disk drill in a tilled, firm seedbed range from 200 N/row for a wide drill (>3.66 m, 12 ft) to 400 N/row for a narrow (<2.44 m, 8 ft) drill. Since rolling resistance is not as dominant in firm, no-till conditions, draft for no-till drills was estimated as 250 N/row plus the coulter draft (320-470 N/row). The proposed drill draft parameters are within the range currently reported by ASAE.

3.1.17 Hoe and Pneumatic Drills

Proposed draft parameters for hoe drills (2,200 to 3,400 N/m of width) and pneumatic drills (2,600 to 4,350 N/m) are based on Kydd et al. (1984). These values are adjusted for soil texture similar to other chisel-type tools. The proposed hoe drill data are in general agreement with the deep furrow grain drill data currently listed by ASAE (1993a).

3.2 INTEGRATION OF TILLAGE DRAFT DATA WITH DAFOSYM

The proposed draft and power data were integrated with DAFOSYM to predict draft, power and fuel consumption for a range of tillage and planting implements as a function of soil texture, tillage depth and speed of operation. Total power required to operate implements was greater than that required to overcome draft. Rotary power, power to overcome rolling resistance and draft power components were calculated separately. Rotary power for implements

Table 3.2. Tillage, planting and seeding implement draft and machine operation parameters used in DAFOSYM.

Implement	Speed km/h	Depth cm	Field efficiency	SI units	Parameters, SI A	B	C
Moldboard Plow	7.2	20	.75	n/cm²	4.20	---	0.037
Coulter-Chisel Plow							
7.5 cm twisted shovel	8.9	20	.85	n/cm²	2.90	0.17	---
Tandem Disk Harrow							
secondary tillage	8.9	10	.85	n/cm²	1.90	0.10	---
Field Cultivator							
w/coil tine harrow	9.7	7.5	.85	n/cm²	2.32	0.11	---
Seedbed Conditioner							
secondary tillage	9.7	7.5	.85	n/cm²	2.57	0.14	---
Manure Injector[1]	7.2	12	.90	---	---	---	---
Rotary Hoe	14.5	---	.85	n/m	500	---	---
Aerator	9.7	---	.85	n/m	4,500	---	---
Corn Planter							
conventional	8.8	---	.65	n/m	1,500	---	---
conservation	8.8	---	.65	n/m	1,500	---	---
zone-till	8.8	---	.65	n/m	3,700	---	---
Grain Drill							
conventional	8.8	---	.70	n/m	1,100	---	---
no-till	8.8	---	.70	n/m	2,900	---	---

with significant rotary power requirements such as manure spreaders was based on published data (Safley and Nye, 1982) and determined by standard procedures (Rotz and Muhtar, 1992). For manure spreaders, row crop planters and seed drills that required considerable power to overcome rolling resistance, implement mass and typical values for soil cone index were used to calculate rolling resistance (ASAE, 1993a). Draft to overcome rolling resistance was included in the draft parameters (Table 3.1) for tillage, planting and seeding implements. Total draft for slurry injector tankers was obtained by first calculating rolling

[1] 11.9 kW (16 hp) per injector shank was added to draft needed to overcome tanker rolling resistance.

resistance and then adding 11.9 kW (16 hp) per injector as indicated by the draft data in Table 3.1.

Major tillage tool draft data were converted to common units (n/cm^2) based on implement configuration for use in DAFOSYM. Minor tillage tool, planting and seeding implement draft were determined per unit width (n/m). The standardized draft parameters used in DAFOSYM are listed in Table 3.2. Total power required for the operation of implements is the sum of implement power components converted to equivalent pto power (ASAE, 1993b). Total engine power required was set greater than total implement power required. Variations in soil and moisture conditions, topography and safety requirements make it necessary to hold some power in reserve to overcome fluctuating load conditions. Twenty percent of the maximum potential power available at the drawbar was held in reserve. Field speeds were limited by machine draft where power requirements were greater than available with the specified power unit. Fuel consumption was modeled using standard procedures (ASAE, 1993a). Fuel use was a function of the ratio of the equivalent pto power required by an operation to the maximum available from the pto.

3.3 DEVELOPMENT OF THE SUITABLE DAY MODEL

A common approach for manure land application is to spread stored manure in the spring prior to planting and in the fall after corn harvest. Since timeliness penalties for corn planting begin to accumulate in early May and soil conditions for tillage and spreading deteriorate rapidly in the fall, an accurate estimate of suitable days is important for livestock producers. Suitable working days are the days available in a scheduled period during which field operations can be performed (Von Bargen et al., 1986). A good estimate of the number of days suitable for field operations helps farm managers select the machinery capable of completing field operations within the time available. The number of suitable days in a time period is influenced by climatic region, soil slope and texture, drainage, operation performed and the use of traction and flotation devices (ASAE, 1993a).

3.3.1 Soil Moisture Budget

A soil moisture budget was developed based on the method of Kiniry and Jones (1986) and was used to predict suitable days for field work. Similar to models developed by other researchers (Rutledge and McHardy, 1968; Selerio and Brown, 1972; Baier, 1973; Tulu et al., 1974; Elliott et al., 1977; Dyer and Baier, 1979; Acharya et al., 1983; von Bargen et al., 1986), soil moisture was calculated for multiple soil layers. Daily temperature, precipitation and solar radiation together with soil characteristics influenced water infiltration, drainage and evaporation. Submodels were added to estimate the date of soil thaw in the spring and the effect of crop residue cover on the rate of soil moisture evaporation.

Soil moisture was tracked in four soil layers: surface to 3 cm (surface to 1.2 in), 3 to 7.6 cm (1.2 to 3 in), 7.6 to 15.2 cm (3 to 6 in) and 15.2 to 100 cm (6 to 39.4 in). Soil moisture in the upper three layers determined suitable days for field work. Since suitable day determinations were not needed from the time corn was planted until corn silage harvest began in the fall, soil moisture extraction from crop growth was not modeled. However, a full season soil moisture balance was maintained by assuming 0.3 cm/d (0.12 in; Shayya and Bralts, 1994) soil moisture was removed by plant growth from June 1 through September 30.

Freezing and thawing of soil are not considered in the soil moisture balance of Kiniry and Jones. Since manure spreading and tillage begin in the spring as soon as soil is trafficable, an estimate of the date of soil thaw based on annual climatic data is needed. A simple model was developed to predict spring soil thaw and initial soil moisture. Soil was considered thawed and at field capacity after the accumulation of fourteen degree days (celsius; Tulu, 1973). A degree day was calculated as the average of the daily maximum and minimum temperatures. If the maximum daily temperature was greater than 7° C (45° F), degree days were accumulated (Selerio and Brown, 1972). If the maximum daily temperature was less than 7° C but greater than 0° C, degree days were accumulated at a reduced rate. If the average daily temperature was less than 0° C (32° F) the soil was assumed to re-freeze and the total accumulation reset to zero but soil was always assumed thawed by April 20.

Water is removed from the soil through infiltration, plant use and evaporation. Early in the spring and late in the fall when a crop is not growing, evaporation is required to draw soil moisture to a level below field capacity. Evaporation is largely influenced by solar radiation, temperature, wind and the interaction of temperature and wind (Brun et al., 1986). Residue cover delays the rate of evaporation. A simple model was developed to describe the effect of crop residue on the rate of moisture evaporation. The rate of Stage 1 evaporation was reduced as a positive linear function of residue cover ranging from no effect at 0% cover to a 50% reduction at 100% residue cover. This rate reduction is a composite of both field and soil core measurements (Bond and Willis, 1969; 1970; Smika, 1983; Brun et al., 1986; Aase and Tanaka, 1987).

3.3.2 Soil Moisture Criteria for a Suitable Day

The main factor determining a suitable day was the trafficability of the soil surface. Trafficable soil could be worked without serious structural damage or excessive compaction (Flores et al., 1990). Soil moisture criteria were compared to the soil moisture level to determine suitable days. A day was determined suitable for field operations if the soil moisture was within acceptable limits. Soil is not generally considered suitable for tillage until the soil to the depth of tillage is below field capacity (Rutledge and McHardy, 1968; Selerio and Brown, 1972; Baier, 1973; Tulu et al., 1974; Elliott et al., 1977; Dyer and Baier, 1979; Acharya et al., 1983; von Bargen et al., 1986), but higher moisture levels are

are considered suitable for some non-tillage operations. Soil moisture at field capacity near the surface was considered suitable for harvest operations (Tulu et al., 1974; Rosenberg et al., 1982) and moisture above field capacity was considered suitable for land application of manure (Witney et al., 1982; McGechan and Cooper, 1994). In the current model, a day was considered suitable if:

$SM_i \leq C_i$ for i = 1, 2, 3

where:

SM_i = available moisture of the ith soil layer as a fraction of field capacity.

C = upper limit of moisture allowable as a fraction of field capacity.

i = 1, 2, 3 refers to the 0-5 cm, 5-10 cm and 10-15 cm soil layers, respectively.

The upper soil moisture limit as a fraction of field capacity (**C** values) used to define suitable days are listed in Table 3.3. The **C** values were specific to soil texture and field operation. Since coarse textured (sandy) soils tend to be less susceptible to soil compaction than fine textured soils (loams and clay loams), greater moisture was allowed in the coarser textured soils.

Higher soil moisture was allowed when there where opportunities to alleviate soil compaction prior to spring planting. Remedial activities included: 1) fall tillage under drier soil conditions, 2) freezing and thawing and 3) spring

Table 3.3 Allowable fraction of field capacity (C_i's) for various soil layers and field operations.

Operation	Soil Layer, i	Clay Loam	Loam	Sandy Loam
Spring Tillage, Planting and Manure Injection	1	0.95	0.97	0.99
	2	0.95	0.97	0.99
	3	0.97	0.985	1.00
Spring Manure Spreading, Fall Tillage and Manure Injection	1	0.98	0.99	1.00
	2	0.98	0.99	1.00
	3	0.99	1.00	1.01
Corn Harvest and Fall Manure Spreading	1	1.02	1.04	1.06
	2	1.02	1.04	1.06
	3	1.00	1.02	1.04

seedbed tillage. Spring tillage and planting are the final operations prior to crop establishment. If the soil is worked when too wet, soil compaction and cloddy seedbeds may result with no suitable opportunities for remedial action. Therefore, the driest soil was required for spring tillage, spring manure injection and planting (Table 3.3). Higher moisture was allowed for fall tillage, fall manure injection and spring surface spreading of manure since soil compaction could be alleviated by either spring tillage or winter freeze-thaw cycles. The greatest soil moisture was allowed in the fall for corn harvest and manure spreading. This higher allowable moisture recognizes the ability of crop residue and root mass to aid trafficability and the opportunity for fall tillage, freezing and thawing and spring tillage to alleviate soil compaction and create a suitable seedbed prior to planting.

3.3.3 Verification of the Suitable Day Model

A comparison of suitable days on a well-drained clay loam soil in Michigan and southern Ontario is listed in Table 3.4. The number of available days predicted by the suitable day model for spring operations was somewhat less than reported by Rosenberg et al. (1982) but greater than that reported by ASAE (1993a) and similar to that reported by McCorquodale et al., (1988). Similarly, the suitable day model predicted somewhat less time available for fall operations than reported by Rosenberg et al. (1982) or McCorquodale et al. (1988) but more days than reported by ASAE (1993a). Since predicted days are influenced by assumptions regarding infiltration rate, organic matter, sand, silt and clay content and other soil parameters, some deviation from other published data is expected.

Soil texture influenced suitable days. More time was available on a coarse textured sandy loam than on a fine textured clay loam. Fine textured soils have greater water holding capacity and tend to drain more slowly than coarse textured soils so more time is needed for infiltration and evaporation to create soil conditions suitable for field work. The greatest difference was late in the fall when cool temperatures and reduced solar radiation reduced evaporation. In the spring there were two to three more days available for tillage on a sandy loam than a clay loam soil. There were four to eight more days available for tillage from October through December on the coarse textured soil. These differences

Table 3.4 Comparison by data source: expected proportion of days suitable for tillage per time period on a well drained, clay loam soil.

	Central Michigan (proposed)	Central Michigan[1]	Southeast Michigan[2]		Southern Ontario[3]	
Probability, %	80	80	50	90	67	75
April 11-20	.25	--	--	--	--	--
April 21-30	.29	.34	.20	--	.36	.23
May 1-10	.51	.66	--	--	.61	.49
May 11-20	.37	.62	--	--	.51	.37
May 21-31	.60	.71	.61	.32	--	--
June 1-15	--	.66	--	--	.60	.50
June 16-30	--	.72	.69	.42	.53	.41
July 1-15	--	.80	--	--	--	--
July 16-31	--	.79	.75	.52	--	--
August 1-15	--	.65	.74	.53	--	--
August 16-31	--	.71	--	--	--	--
September 1-15	.65	.75	.70	.35	--	--
September 16-30	.45	.68	--	--	.80	.70
October 1-15	.50	.64	.59	.26	.74	.64
October 16-31	.48	.58	--	--	.70	.60
November 1-15	.26	.42	.42	.06	.59	.48
November 16-30	.05	.11	.07	.00	.48	.43

are similar to those reported by other researchers for Michigan and nearby states (Tulu et al., 1974; Parsons and Doster, 1980; Rosenberg et al., 1982; ASAE, 1993b).

Crop residue reduced the number of suitable days for field work (Table 3.5). The greatest effect was early in the spring and late in the fall when temperatures and solar radiation were relatively low. On a clay loam soil, eighty percent residue cover reduced suitable days for tillage in April and May by about three. This difference is similar to that reported by Elliott et al. (1977). The

[1] Rosenberg et al., 1982.
[2] ASAE, 1993a.
[3] McCorquodale et al., 1988.

Table 3.5 Predicted suitable days (80% probability) for tillage, planting, manure spreading and harvest in central Michigan with three soils and three levels of crop residue.

	April	May	June	July	Aug	Sept	Oct	Nov	Dec
CONVENTIONAL TILLAGE [1]									
Till, Plant, Inject									
Clay loam	7.8	18.0	18.4	22.3	19.3	17.7	16.4	5.8	0.0
Loam	9.0	19.3	19.2	23.5	21.0	19.2	18.0	7.0	0.0
Sandy loam	9.7	21.1	19.8	23.8	21.8	20.3	19.9	12.4	8.3
Harvest, Spreading									
Clay loam	9.0	19.9	20.1	25.8	23.2	21.3	21.2	12.0	6.6
Loam	9.9	21.1	21.2	26.2	23.8	21.7	21.8	14.4	11.1
Sandy loam	11.0	21.8	20.9	24.9	22.8	20.8	21.7	15.4	13.4
MULCH TILLAGE [2]									
Till, Plant, Inject									
Clay loam	5.7	16.5	17.0	20.5	18.1	16.4	14.7	4.5	0.0
Loam	7.8	18.5	18.2	22.6	19.6	18.6	16.4	5.5	0.0
Sandy loam	8.6	20.3	18.9	23.5	20.9	19.4	18.9	11.0	7.0
Harvest, Spreading									
Clay loam	7.9	18.5	18.4	24.6	22.3	20.0	19.8	9.9	5.2
Loam	8.6	20.5	19.8	25.4	22.8	21.0	21.3	13.1	9.9
Sandy loam	10.1	21.1	20.2	24.3	22.1	20.4	20.8	14.0	12.8
NO-TILL [3]									
Till, Plant									
Clay loam	4.6	15.2	15.4	19.5	16.9	15.0	12.6	2.7	0.0
Loam	7.0	16.8	16.5	21.0	18.9	17.2	14.1	3.8	0.0
Sandy loam	8.0	19.0	17.8	22.2	20.2	18.7	18.0	9.9	6.0
Harvest, Spreading									
Clay loam	5.5	16.9	17.4	23.2	21.3	19.3	17.9	8.8	3.7
Loam	7.9	18.7	18.4	23.9	22.1	19.9	19.8	11.0	8.6
Sandy loam	9.4	19.9	19.1	23.2	21.0	19.5	19.7	12.9	12.0

reduction in suitable days was not as great on the coarse textured sandy loam due to the lower moisture holding capacity of that soil. Eighty percent cover reduced available time by about two days in April and May. Since harvest, tillage and

[1] 10% residue cover in the fall, 0% cover in the spring.
[2] 50% residue cover in the fall, 40% cover in the spring.
[3] 90% residue cover in the fall, 80% cover in the spring.

manure spreading occured on untilled corn residue, no reduction in suitable days from residue cover was predicted between tillage systems for fall operations.

4. PROCEDURE

Many of the questions that farmers have at the systems engineering level relate to the capacity, cost, labor requirements and compatibility of alternative tillage and manure handling subsystems. One of the objectives in the development of the suitable day, tillage and manure handling submodels of DAFOSYM was to create a flexible model that could be used to describe, evaluate and compare a wide range of tillage, planting, manure storage, transport and application methods. Tillage and planting systems compared include conventional, mulch-till and modified no-till. Land application methods included liquid irrigation, surface spreading or injection with slurry tankers and daily hauling with a V-tank spreader. Other parameters that could be varied included land area, crop rotation, number of animals, feeding strategy, length of workday and number of simultaneous field operations. This range of options provides a flexible model that can generate data suitable for a specific farm or can be used in a more generalized way to evaluate and compare alternative farming systems.

To illustrate the ability of the model to describe, evaluate and compare a wide range of tillage and manure handling options, four manure handling and three tillage systems were modeled and compared on five synthesized, representative dairy farms. The farms included dairies milking 60, 150, 250, 400 and 800 cows. The analysis was performed over 26 years of East Lansing, Michigan weather conditions to obtain a long-term evaluation of systems.

4.1 HERD, CROP AND PRICE INFORMATION

The dairy herds included Holstein cows and replacement stock. Cows in their first lactation formed 35% and dry cows 15% of the milking herd. The number of young stock on each farm was selected to provide all replacements (Table 4.1). Potential annual milk production was set at 10,000 kg/cow (22,000 lb/cow). This yield level could only be attained with the addition of fat to the diet and fat was not fed so forage quality was the primary constraint to milk production. Higher forage quality increased milk production. Corn and alfalfa were the two crops grown on all farms with approximately half of the farm land area in each. No crop land was set aside for the purpose of manure disposal during the growing season. The soil was a medium loam with a total water holding capacity of 200 mm (7.9 in). Crop areas and predicted average post-harvest yields for each representation are listed in Table 4.1.

Herbicide costs for first year alfalfa following corn and first year corn following alfalfa were increased to allow a burn-down treatment for grass control. Seeding rates were increased by 5% with the no-till system for both corn and alfalfa to compensate for decreased emergence or insect damage. Annual costs for seed, chemicals and fertilizer are listed in Table 4.2.

Alfalfa and corn silage harvest procedures were similar for all farms. A four cutting system was used for alfalfa and harvests were begun at a bud stage of development for first and second cuttings and an early flower stage for third

Table 4.1 Major descriptive parameters of the representative farms used to evaluate and compare tillage and manure management systems.

	Representative Farm				
	60-cow	150-cow	250-cow	400-cow	800-cow
Livestock					
Lactating cows	51	128	212	340	680
Dry cows	9	23	38	60	120
Replacements over one year old	23	57	94	150	300
Replacements under one year old	25	63	100	160	320
Alfalfa					
Land area	32 ha (79 ac)	75 ha (185 ac)	125 ha (308 ac)	200 ha (494 ac)	400 ha (988 ac)
Harvest system	Hay & silage	Hay & silage	Hay & silage	Hay & silage	Hay & silage
Number of cuttings	4	4	4	4	4
Average post harvest yield	10.7 t DM/ha	10.9 t DM/ha	10.8 t DM/ha	10.7 t DM/ha	10.8 t DM/ha
	4.8 ton DM/ac	4.9 t DM/ac	4.8 ton DM/ac	4.8 ton DM/ac	4.8 ton DM/ac
Corn					
Land area	35 ha (86 ac)	70 ha (173 ac)	125 ha (308 ac)	200 ha (494 ac)	400 ha (988 ac)
Average grain yield	5.9 t DM/ha	5.9 t DM/ha	5.9 t DM/ha	5.9 t DM/ha	5.9 t DM/ha
	108 bu/ac	108 bu/ac	108 bu/ac	108 bu/ac	108 bu/ac
Average silage yield	13.6 t DM/ha	13.6 t DM/ha	13.7 t DM/ha	13.6 t DM/ha	13.6 t DM/ha
	5.0 ton DM/ac	5.0 ton DM/ac	5.0 ton DM/ac	5.0 ton DM/ac	5.0 ton DM/ac

Table 4.2 Economic parameters and prices assumed for various system inputs and outputs in the representative farm analysis.

Parameter	Value
Labor wage rate	$9.35/h
Diesel fuel price	$0.28/liter ($1.06/gallon)
Electricity price	$0.08/kW-h
Corn drying cost	$1.18/pt./t ($1.07/pt./ton)
Corn grain elevation and storage cost	$9.40/t DM ($8.54/ton DM)
Land rental rate	$125/ha ($50/acre)
Milk price	$0.28/liter ($12.5/cwt)
Fertilizer prices	
-Nitrogen	$0.31/kg ($0.14/lb)
-Phosphorous	$0.42/kg ($0.19/lb)
-Potassium	$0.24/kg ($0.11/lb)
Annual cost of seed and chemicals:	
conventional and mulch tillage	
-Establishment year alfalfa	$203/ha ($82/acre)
-Established alfalfa	$15/ha ($6/acre)
-Corn following alfalfa	$116/ha ($47/acre)
-Corn following corn	$156/ha ($63/acre)
modified no-till	
-Establishment year alfalfa	$235/ha ($95/acre)
-Established alfalfa	$15/ha ($6/acre)
-Corn following alfalfa	$133/ha ($54/acre)
-Corn following corn	$156/ha ($63/acre)
Selling price of feeds	
-Corn grain	$113/t ($103/ton) DM
-High-moisture corn	$102/t ($93/ton) DM
-Alfalfa hay	$90/t ($82/ton) DM
-Corn silage	$66/t ($60/ton) DM
Buying price of feeds and bedding	
-Soybean meal	$260/t ($236/ton) DM
-Corn grain	$118/t ($107/ton) DM
-Alfalfa hay	$100/t ($91/ton) DM
-Chopped straw bedding	$60/t ($55/ton)
Custom operation rates	
-Corn grain harvest, transport and unload	$65/ha ($26/acre)
Economic life	
-Storage structures	20 yr
-Machinery	10 yr
Salvage value	
-Storage structures	0%
-Machinery	10%
Real interest rate	6%/yr

and fourth. Harvest dates for the first three cuttings were within five days of May 30, July 6, and August 23. Weather permitting, fourth cutting was begun on October 15. Alfalfa harvest days were not available for tillage or manure spreading. First, third and fourth cuttings of alfalfa were harvested as silage with only second cutting baled as hay. Chopping was begun when the crop had dried to 65% moisture. Hay was harvested at less than 20% moisture in round bales and stored in a shed.

Weather permitting, corn silage harvest was begun on September 12 with silage preserved at 65 to 70% moisture (dough to glaze stage of maturity). High-moisture corn harvest was begun on October 1 and stored at 25 to 30% moisture. Harvest of dried shelled corn was begun October 10 with grain dried to 15½% moisture. Corn grain harvest was custom hired and did not interfere with tillage or manure spreading. Alfalfa silage, corn silage and high-moisture shelled corn were stored in bunker or concrete-stave silos (Tables 4.3, 4.4 and 4.5). Other corn grain was dried, elevated and stored off the farms. Silage and concentrates were fed as a total mixed ration (TMR) using a mobile feed mixer and a skid-steer loader. Hay was fed from a self-feeding rack. Feeds not used during the year following harvest were sold as excess feed.

Tillage and manure spreading on the land harvested as corn silage was begun upon completion of corn silage harvest. Manure spreading and tillage of

Table 4.3 Major machines and structures used for crop harvest and storage on the representative 60 and 150-cow farms.

Machine or storage type	67 ha (165 acre) 60-Cow Farm Size	No.	Price($)	145 ha (358 acre) 150-Cow Farm Size	No.	Price($)
FEED HARVEST AND STORAGE						
Mower-conditioner	2.7 m (9 ft)	1	10,800	3.7 m (12 ft)	1	15,200
Tandem rake	5.4 m (18 ft)	1	8,500	5.4 m (18 ft)	1	8,500
Round baler	small (4X4)	1	10,000	medium (5X4)	1	15,200
Bale loader/grabber	large	1	6,300	large	1	6,300
Round bale wagon	3.3 t (3.6 ton)	1	4,000	4.9 t (5.4 ton)	1	4,000
Forage harvester	12 t (13.2 ton) DM/h	1	20,100	12 t (13.2 ton) DM/h	1	20,100
Forage blower	10 t (11 ton) DM/h	1	3,800	10 t (11 ton) DM/h	1	3,800
Forage wagons	6 t (6.6 ton)	2	8,650	6 t (6.6 ton)	2	8,650
Feed mixer	4.5 t (5 ton) DM/h	1	12,600	12 t (13.2 ton) DM/h	1	22,500
Hay storage shed	99 t (110 ton) DM	1	11,800	200 t (220 ton) DM	1	20,125
Alfalfa bunker	---	-	---	490 t (540 ton) DM	1	24,950
Alfalfa silo	180 t (198 ton) DM	1	23,000	---	-	---
Corn silage bunker	---	-	---	490 t (540 ton) DM	1	24,950
Corn silage silo	159 t (144 ton) DM	1	19,350	---	-	---
High-moist. corn silo	---	-	---	262 t (289 ton) DM	1	14,800

Table 4.4 Major machines and structures used for crop harvest and storage on the 250 and 400-cow representative farms.

Machine or 2 storage type	250 ha (616 acre) 250-Cow Farm Size	No.	Price($)	400 ha (988) acre) 400 Cow Farm Size	No.	Price($)
FEED HARVEST AND STORAGE						
Mower-conditioner	self-prop. 4.3 m (14 ft)	1	34,200	3.7 m (12 ft)	2	34,200
Tandem rake	5.4 m (18 ft)	1	8,500	5.4 m (18 ft)	2	8,500
Round baler	large (6X4)	1	17,700	large (6X4)	2	17,700
Bale loader/grabber	large	1	6,300	large	2	6,300
Round bale wagon	4.9 t (5.4 ton)	1	4,000	4.9 t (5.4 ton)	2	4,000
Forage harvester	18 t (19.8 ton) DM/h	2	30,450	18 t (19.8 ton) DM/h	2	30,450
Forage blower	10 t (11 ton) DM/h	1	3,800	10 t (11 ton) DM/h	1	3,800
Forage wagons	6 t (6.6 ton)	4	8,650	6 t (6.6 ton)	4	8,650
Feed mixer	12 t (13.2 ton) DM/h	1	22,500	12 t (13.2 ton) DM/h	2	22,500
Hay storage shed	334 t (367 ton) DM	1	31,900	500 t (550 ton) DM	1	95,000
Alfalfa bunker	385 t (424 ton) DM	2	21,275	1150 t (1265 ton) DM	1	48,050
Corn silage bunker	645 t (711 ton) DM	1	30,375	1150 t (1265 ton) DM	1	48,050
High-moist. corn silo	323 t (356 ton) DM	1	19,350	403 t (444 ton) DM	1	34,050

Table 4.5 Major machines and structures for crop harvest and storage on the representative 800-cow farm.

Machine or storage type	800 ha (1,975 acre) 800-Cow Farm Size	No.	Price($)
FEED HARVEST AND STORAGE			
Mower-conditioner	self-prop. 4.3 m (14 ft)	3	34,200
Tandem rake	5.4 m (18 ft)	3	8,500
Round baler	large (6X4)	3	17,700
Bale loader/grabber	large	3	6,300
Round bale wagon	4.9 t (5.4 ton)	3	4,000
Forage harvester	18 t (20 ton) DM/h	3	30,450
Forage blower	10 t (11 ton) DM/h	1	3,800
Forage wagons	6 t (6.6 ton)	6	8,650
Feed mixer	12 t (13.2 ton) DM/h	3	22,500
Hay storage shed	1100 t (1211 ton) DM	1	95,000
Alfalfa bunker	1435 t (1579 ton) DM	1	48,050
	1150 t (1265 ton) DM	1	48,050
Corn silage bunker	1150 t (1265 ton) DM	2	48,050
High-moist. corn silo	692 t (763 ton) DM	1	34,050

land harvested for high-moisture or dried corn began as land became available following harvest.

Feed rations for each of six animal groups (three lactation groups, dry cows, older heifers and younger heifers) were determined by a linear program embedded in DAFOSYM. The linear program maximizes forage intake while minimizing the cost of purchased feeds to establish rations (Rotz et al., 1989). The total digestible nutrient (TDN) contents of farm-grown alfalfa and corn were predicted by the growth, harvest and storage submodels of DAFOSYM. Average values were assumed for purchased feeds.

The manure production and utilization model used in DAFOSYM has been described by Borton et. al (1995). Manure production was modeled as feed dry matter (DM) consumed minus the digestible DM used by the animals plus urine

DM. Manure DM was increased by 3% of the feed DM intake to account for feed losses and further increased to account for the bedding dry matter used. To determine the quantity of manure handled, moisture contents of 87%, 91% and 94% were assumed for semi-solid, slurry and liquid irrigation systems, respectively.

The manure nutrient value was determined through a mass balance of all the animal groups with manure nutrients equal to the nutrient intake minus nutrients contained in milk and body growth. Nitrogen intake was determined from the crude protein content of the feed consumed. Typical values of phosphorus (P) and potassium (K) in feeds as published by the National Research Council (1988) were used together with nutrients in feed supplements to predict P and K in manure (Borton et al., 1995).

Prices were set to reflect the long-term relative values for the various farm inputs and outputs in 1994 dollars. Prices for milk, excess feed and various farm inputs are listed in Table 4.2 and those for machinery and storage structures are listed in Tables 4.3, 4.4 and 4.5. Machinery repair and maintenance costs were determined as a function of price and accumulated use (ASAE, 1993a). Diesel fuel was priced at $0.28/liter ($1.06/gal) and the labor wage rate was $9.35/h. A real interest rate (approximately nominal rate minus inflation) of 6% annually was used for investments. Machines and structures were depreciated over 10 and 20 years to salvage values of 10% and 0% of their initial value, respectively.

DAFOSYM follows a partial budget format and accounts for all costs associated with manure storage and land application, tillage, planting, growing, harvesting and storing of feed and feeding the milking herd and young stock. A net return over tillage, feed and manure costs is calculated as the difference between the income from milk sales and the net cost of producing the feed, feeding the animals and handling the manure. Additional costs for operations not modeled in DAFOSYM including animal housing, milking center, livestock expenses, utilities and herd health were estimated (Table 4.6) from Nott and Carter (1993), Bickert (1994) and Bickert and Stowell (1994) to determine a net return (Table 5.8).

4.2 NUTRIENT AVAILABILITY AND LOSS

Nitrogen losses during collection, storage and application were modeled in DAFOSYM by Borton et al. (1995). Volatile N was assumed to be 35% of the total N after collection and loss of volatile N during storage was a function of loading method, rate of loading, wind speed and ambient temperature. Loss of volatile N from manure applied to crop land was a function of time between spreading and incorporation. All volatile N applied to alfalfa land was assumed lost. Of the organic N entering the soil, 30% was considered available to the crop during the first year with one-half of the remaining amount becoming available in each succeeding year. Losses of P and K were assumed to be 5% of that contained in fresh manure.

Table 4.6 Major dairy costs ($/cow-yr)[1] above the net return over feed, manure and tillage costs calculated by DAFOSYM.

	60-cow	150-cow	250-cow	400-cow	800-cow
Animal housing[2]	123	123	123	123	123
Milking center[3]	271	108	98	81	81
Misc. eqp't. & structures[4]	55	26	23	21	16
Livestock expenses[5]	455	474	500	500	500
Utilities[6]	74	61	61	61	61
Herd labor[7]	468	464	449	411	365
TOTAL	**1,446**	**1,260**	**1,254**	**1,197**	**1,146**

The nutrient value of the manure produced by a 636 kg (1,400 lb) dairy cow is about $82/yr (Jacobs, 1991). System losses and inefficient use of the nitrogen contained in manure spread on alfalfa land reduced the value of the manure on the representative farms. About forty-five percent of the manure produced was spread on alfalfa land. Although nutrient carry-over provided some value for corn production, most of this nitrogen was lost.

[1] Cash flow basis, before tax costs. Animal housing depreciated over 20 years and milking center over 12 years to 0% salvage value. Six percent real interest rate (nominal minus inflation). Annual taxes, insurance and repair and maintenance estimated as 2.25% of purchase price. Labor @ $9.35/h.

[2] Source: Bickert, 1994. Free stall and dry cow housing purchase price @ $800/cow, animal care facility @ $50/cow, replacement housing @ $350/cow and commodity shed @ $70/cow.

[3] Source: Bickert, 1994. Includes holding pen, crowd gate, parlor, milking equipment and bulk tanks @ $15,000 per milking unit. Double four (D-4) herringbone parlors were used on the 60 and 150-cow farms and D-6, D-8 and D-16 parlors were used on the 250, 400 and 800-cow farms, respectively.

[4] Includes water wells, back-up electrical, computers and software.

[5] Source: Nott and Carter, 1994. Includes breeding and herd health, trucking, livestock supplies, DHIA, registration and related expenses.

[6] Source: Nott and Carter, 1994.

[7] Calculated as herd labor per cow (Nott and Carter, 1994) minus labor for feeding and alley scraping calculated in DAFOSYM.

4.3 CROP NUTRIENT REQUIREMENTS

Crop nutrient requirements as modeled in DAFOSYM were based on nutrients removed as a function of yield (Borton et al., 1995). Crop nutrient requirements were met first by crop rotation carryover effects, then by manure nutrients and finally by purchased fertilizer. Manure was applied on each crop until the most limiting of N, P or K was met with a small over-application of nutrients allowed. Rotated alfalfa land was first used for corn silage production and then for corn grain production. The N requirement was reduced by 112 kg/ha (100 lb/ac) on this land following alfalfa and yields were increased by 15% as a rotation effect. Manure was allocated first to corn silage land, next to corn grain land, then to new alfalfa seedings with the remainder spread on existing alfalfa fields. Crop nutrient requirements not met by manure were applied as commercial fertilizer during the planting operation.

4.4 TILLAGE SYSTEMS

Three tillage systems offering a range in tillage and planting practices were modeled. Conventional tillage included fall tillage with moldboard plowing of all land to be planted in the spring. In the spring, corn ground was disked once and field cultivated once before planting. Alfalfa ground was disked twice and field cultivated twice before seeding. A list of tillage and planting equipment used on each farm is included in Tables 4.7, 4.8 and 4.9.

Table 4.7 Major machines and structures used for planting and manure storage on the 60 and 150-cow representative farms.

Machine or storage type	67 ha (165 acre) 60-Cow Farm Size	No.	Price($)	145 ha (358 acre) 150-Cow Farm Size	No.	Price($)
TRACTORS AND LOADERS						
Conventional and mulch-tillage						
Tractors	35 kW (47 hp), used	1	4,000	35 kW (47 hp), used	2	4,000
	50 kW (67 hp)	1	27,150	65 kW (87 hp)	2	37,200
	65 kW (87 hp) [1]	1	37,200	80 kW (108 hp)	1	45,750
Skid-steer loader	small	1	10,350	large	1	18,450
TILLAGE AND PLANTING						
Conventional tillage						
Moldboard plow	1.4 m (4.5 ft)	1	7,300	1.6 m (5.3 ft)	1	8,100
Tandem disk	2.7 m (9.0 ft)	1	3,950	4.9 m (16 ft)	1	9,750
Field cultivator	3.7 m (12.0 ft)	1	7,550	5.5 m (18 ft)	1	11,250
Grain drill	2.4 m (8.0 ft)	1	5,750	2.4 m (8 ft)	1	5,750
Conventional planter	3.0 m (10.0 ft)	1	12,000	3.0 m (10 ft)	1	12,000
Mulch-tillage						
Coulter-chisel plow	2.0 m (6.6 ft)	1	3,825	2.0 m (6.6 ft)	1	3,825
Seedbed conditioner	4.0 m (13 ft)	1	8,820	4.0 m (13 ft)	1	8,820
Grain drill	2.4 m (8.0 ft)	1	5,750	2.4 m (8 ft)	1	5,750
Conservation planter	3.0 m (10.0 ft)	1	13,000	3.0 m (10 ft)	1	13,000
Modified no-till						
Aerator	2.4 m (8 ft)	1	5,725	3.7 m (12 ft)	1	7,800
Rotary hoe	4.5 m (15 ft)	1	3,500	4.6 m (15 ft)	1	3,500
No-till drill (used)	2.4 m (8.0 ft)	1	5,750	2.4 m (8 ft)	1	5,750
Zone-till planter	3.0 m (10 ft)	1	17,400	3.0 m (10 ft)	1	17,400
MANURE HANDLING AND STORAGE						
Semi-solid, 3 day storage						
Slab/buckwall	60 m^2 (645 ft^2)	1	1,600	150 m^2 (1610 ft^2)	1	3,900
V-tank spreader	7.9 t (2100 gal)	1	15,850	9.8 t (2600 gal)	1	19,100
Slurry, 7 month storage						
Clay-lined storage pit	2140 m^3 (566,000 gal)	1	30,000	5237 m^3 (1.4 mil. gal)	1	47,500
Slurry pump/agitator	340 t/h (1500 gpm)	1	7,200	450 t/h (2000 gpm)	1	9,000
Slurry spreader	8.3 t (2200 gal)	1	8,750	10.2 t (2700 gal)	1	10,350
or						
Slurry injection	8.3 t (2200 gal)	1	11,400	10.2 t (2700 gal)	1	13,950
Liquid, 7 month storage						
Clay-lined storage pit	2840 m^3 (752,000 gal)	1	34,000	6980 m^3 (1.86 mil. gal)	1	57,500
Slurry pump/agitator	340 t/h (1500 gpm)	1	7,200	450 t/h (2000 gpm)	1	9,000
Chopper pump (used)	---	1	1,950	---	1	1,950
Pressure pump	136 t/h (600 gpm)	1	4,500	136 t/h (600 gpm)	1	4,500
Pipe (used)	500 m (1640 ft)	-	3,000	750 m (2460 ft)	-	4,550
Traveler w/hose (used)	---	1	5,700	---	1	5,700

[1] An 80 kW (108 hp) tractor was used if manure was injected.

Table 4.8 Major machines and structures used for planting and manure storage on the 250 and 400-cow representative farms.

Machine or storage type	250 ha (616 acre) 250-Cow Farm Size	No.	Price($)	400 ha (988 acre) 400-Cow Farm Size	No.	Price($)
TRACTORS AND LOADERS						
Tractors	35 kW (47 hp), used	3	4,000	35 kW (47 hp), used	3	4,000
	65 kW (87 hp)	2	37,200	65 kW (87 hp)	2	37,200
	100 kW (134 hp)	2	56,850	80 kW (108 hp)	2	45,750
	---	-	---	120 kW (161 hp)	2	68,400
Skid-steer loader	large	2	18,450	large	2	18,450
TILLAGE AND PLANTING						
Conventional tillage						
Moldboard plow	2.3 m (7.5 ft)	1	10,500	2.8 m (9 ft)	1	12,500
Tandem disk	5.5 m (18 ft)	1	12,050	7.3 m (24 ft)	1	16,750
Field cultivator	6.4 m (21 ft)	1	13,350	8.5 m (28 ft)	1	17,600
Grain drill	3.7 m (12 ft)	1	8,650	3.7 m (12 ft)	1	8,650
Conventional planter	4.6 m (15 ft)	1	16,500	6.1 m (20 ft)	1	20,500
Mulch-tillage						
Coulter-chisel plow	2.7 m (9 ft)	1	5,350	3.4 m (11 ft)	1	6,900
Seedbed conditioner	5.8 m (19 ft)	1	14,850	7.6 m (25 ft)	1	17,900
Grain drill	3.7 m (12 ft)	1	8,650	3.7 m (12 ft)	1	8,650
Conservation planter	4.6 m (15 ft)	1	18,000	6.1 m (20 ft)	1	22,250
Modified no-till						
Aerator	4.9 m (16 ft)	1	9,800	6.1 m (20 ft)	1	12,800
Rotary hoe	6.1 m (20 ft)	1	4,800	6.1 m (20 ft)	1	4,800
No-till drill (used)	2.4 m (8 ft)	1	5,750	4.6 m (15 ft)	1	10,000
Zone-till planter	4.6 m (15 ft)	1	24,500	6.1 m (20 ft)	1	31,000
MANURE HANDLING AND STORAGE						
Semi-solid, 3 day storage						
Slab/buckwall	240 m^2 (2580 ft^2)	1	6,500	387 m^2 (4160 ft^2)	1	20,800
V-tank spreader	10.9 t (2900 gal)	1	21,000	10.9 t (2900 gal)	1	21,000
Slurry, 7 month storage						
Clay-lined storage pit	8835 m^3 (2.27 mil. gal)	1	67,250	14040 m^3 (3.7 mil. gal)	1	96,500
Slurry pump/agitator	450 t/h (2000 gpm)	1	9,000	450 t/h (2000 gpm)	1	9,000
Slurry spreader	12.5 t (3300 gal)	2	12,300	15.1 t (4000 gal)	2	14,500
or						
Slurry injection	12.5 t (3300 gal)	2	15,850	15.1 t (4000 gal)	2	18,100
Liquid, 7 month storage						
Clay-lined storage pit	11730 m^3 (3.1 mil. gal)	1	83,700	18700 m^3 (5 mil. gal)	1	122,700
Slurry agitator	450 t/h (2000 gpm)	1	9,000	450 t/h (2000 gpm)	1	9,000
Chopper pump (used)	---	1	1,950	---	1	1,950
Pressure pump	136 t/h (600 gpm)	1	4,500	136 t/h (600 gpm)	1	4,500
Auxiliary pump	---	-	---	136 t/h (600 gpm)	1	4,500
Pipe (used)	1000 m (3280 ft)	-	6,000	2000 m (6560 ft)	-	12,150
Traveler w/hose (used)	---	1	5,700	---	1	5,700

Table 4.9 Major machines and structures used for tillage, planting and manure storage on the 800-cow representative farm.

Machine or storage type	800 ha (1,976 acre) 800-Cow Farm Size	No.	Price($)
TRACTORS AND LOADERS			
Tractors	35 kW (47 hp),	6	4,000
	65 kW (87 hp)	3	37,200
	80 kW (108 hp)	3	45,750
	120 kW (161 hp)	4	68,400
Skid-steer loader	large	3	18,450
TILLAGE AND PLANTING			
Mulch-tillage			
Coulter-chisel plow	3.4 m (11 ft)	2	6,900
Seedbed conditioner	7.6 m (25 ft)	2	17,900
Grain drill	4.9 m (16 ft)	1	11,500
Conservation planter	9.1 m (30 ft)	1	31,500
MANURE HANDLING AND STORAGE			
Semi-solid, 3 day storage			
Slab/buckwall	773 m^2 (8320 ft^2)	1	20,800
V-tank spreader	10.9 t (2900 gal)	2	21,000
Slurry, 7 month storage			
Clay-lined storage pit	28000 m^3 (7.4 mil. gal)	1	157,400
Slurry pump/agitator	450 t/h (2000 gpm)	1	9,000
Slurry spreader	15.1 t (4000 gal)	4	14,500
or			
Slurry injection	15.1 t (4000 gal)	4	18,100
Liquid, 7 month storage			
Clay-lined storage pit	37400 m^3 (9.9 mil. gal)	1	210,000
Slurry agitator	large	1	9,000
Chopper pump, used	---	2	1,950
Pressure pump	136 t/h (600 gpm)	2	4,500
Auxiliary pump	136 t/h (600 gpm)	2	4,500
Pipe, used	5000 m (16,400 ft)	-	30,350
Traveler w/hose, used	---	2	5,700

Mulch-tillage included primary tillage with a coulter-chisel plow in the fall and spring seedbed tillage with a combination disk/field cultivator/coil-tine harrow. Land to be planted to corn required one pass for manure incorporation and seedbed preparation in the spring while alfalfa land was worked twice prior to seeding.

A modified no-till system was used which included fall tillage with a rolling tine aerator. The aerator buried very little residue yet loosened the soil, improved water infiltration and helped alleviate shallow soil compaction. When manure was irrigated a rotary hoe was used in the spring to speed drying of the soil surface. Specialized no-till drills using coulters mounted in front of the furrow openers to cut through surface residue and till a narrow band of soil were used. Zone-till planters using a gang of three fluted coulters to till a band of soil 15-30 cm (6-12 in.) wide for each seed furrow were used.

Residue cover on corn ground following grain harvest was assumed to be 65%, consistent with the long-term average grain yield of 7,300 kg/ha (116 bu/ac). The rolling-tine aerator reduced residue cover to 60%, chisel plowing reduced cover to 35% and all residue was buried by moldboard plowing. Residue cover was assumed to decrease by 5 percentage units over winter leaving 0%, 30% and 55% cover in the spring for conventional, mulch-till and modified no-till systems, respectively.

Manure spreading was begun in the spring as soon as the soil was thawed and soil moisture was suitable. Weather permitting, spring disking was allowed to begin April 10 and field cultivating April 20. Seedbed tillage with mulch-till and rotary hoeing with modified no-till was allowed to begin April 20. Alfalfa seeding could begin April 20 and corn planting May 1 with each tillage system.

Fall manure spreading and tillage began after corn silage harvest and continued as land became available following harvest of high-moisture corn or corn grain.

4.5 MANURE HANDLING SYSTEMS

Four manure storage and handling systems typical of Michigan farms using free-stall housing were modeled: a system of short-term (3 day) storage with frequent hauling and three systems using long-term storage: 1) slurry tanker spreading 2) slurry tanker injection and 3) liquid irrigation. Manure handling rates were a composite of rates reported in the literature or measured by the author on the farms of experienced dairy producers. A description of the storage structures and equipment used is listed in Tables 4.7, 4.8 and 4.9.

Short-term storage with daily hauling is among the most common of manure handling systems in Michigan. A V-bottom tanker was used for daily hauling of semi-solid (13% DM) manure. Manure was removed from the barn with a tractor mounted scraper and the spreader was loaded directly from a push-off ramp. A three day storage capacity was provided using a concrete slab with a buckwall. A full spreader was always hauled to the field. A suitable day was not required for spreading with this system.

Manure was removed from long-term storage by irrigation (6% DM) or hauling with top loaded slurry tankers (9% DM). One-half of the annual manure production was spread in the spring with the remainder spread in the fall, but seven months storage capacity in a clay-lined pit was provided. The excess storage capacity increased annual storage costs about 12%, but it helped prevent the need to spread on wet soil and provided flexibility in the tillage and spreading schedule. Pit agitation and tanker loading were with a tractor powered pump/agitator. Pit agitation was begun two hours prior to the start of spreading and then continued only during tanker loading. Agitation was continuous during irrigation.

The average hauling distance for manure spreading on the 60-cow (0.5 km, 0.3 mi), 150-cow (0.8 km, 0.5 mi) and 250-cow (1 km, 0.6 mi) herds was based on an average travel distance with contiguous crop acreage and centrally located storage structures. The larger farms were not assumed to have a contiguous land base. The average hauling distance for the 400-cow farm was 2 km (1.25 mi) and 3 km (1.9 mi) for the 800-cow farm. When manure was irrigated, a pressure pump capable of pumping up to 1 km (0.61 mi) was located at the storage pit. One auxiliary pump was added to pump manure up to 2 km (1.25 mi) on the 400-cow farm and two auxiliary pumps were added for the 3 km (1.9 mi) pumping distance covered on the 800-cow farm. Each manure handling option was compatible with conventional and mulch-tillage. However, slurry injection was not an option with modified no-till since slurry injectors were disruptive of the soil surface and additional tillage was required to level the surface and prepare a seedbed. Tanker spreading, irrigation and daily hauling with a V-tank spreader were compared in the modified no-till systems.

Manure hauled daily and all manure under no-till management was assumed to be left on the surface more than 15 days. Injected slurry was incorporated immediately. Surface spread slurries and irrigated liquid were incorporated within three days of spreading. Phosphorus and potassium were considered stable and available for crop growth regardless of placement or time between spreading and incorporation. Nitrogen, however, was subject to volatilization losses in the barn, during storage and after spreading (Borton et al., 1995). A longer delay in incorporation led to greater loss of volatile N.

4.6 SELECTION OF TILLAGE, PLANTING AND MANURE HANDLING EQUIPMENT

Tractor power, spreader and tillage equipment capacity were chosen by first selecting the tractor power and forage harvester capacity needed for the most economical return to the forage harvesting operation. Tillage equipment was then chosen as the largest implement possible at the designated depth and speed of operation based on the tractor power available (Table 3.1) but implement width was reduced if net return could be increased without creating delays in subsequent tillage and planting operations.

Safety in transport is a major concern when hauling large tankers and spreaders. Tanker and spreader capacities were chosen based on both mass and power requirements. Tankers and spreaders were selected such that the mass of the loaded implement was not greater than two times the tractor mass. Tractor mass was estimated as 80 kg/pto-kW (130 lb/pto-hp). When additional power was needed to accommodate injector draft, tractor power was increased without increasing tanker capacity.

4.7 SIMULATION PROCEDURE

Farmers strive to finish fall tillage by mid-November since in most years few days are suitable after that time. In the spring, timely planting is important since corn grain and silage yields and corn silage quality declines rapidly if planting is delayed beyond May 10. Simulation of 60, 150, 250, 400 and 800-cow representative farms was used to compare the costs and performance of conventional, mulch-till and modified no-till planting systems and their interaction with various manure handling systems. Manure application alternatives included V-tank transport of semi-solids, tanker spreading or tanker injection of manure slurry and liquid irrigation. To demonstrate the effect of the scheduled field operations and length of work day on timeliness of major field operations, the number of simultaneous operations and length of workday were varied.

5. RESULTS AND DISCUSSION

The expanded DAFOSYM model provides a flexible and useful tool for comparing the long-term performance and economics of tillage and manure handling systems and their interaction with feed production on dairy farms. Although DAFOSYM offers a wide range of system options, many assumptions were made to simplify the analysis. Labor, interest and depreciation rates were the same for all farms. Animal housing and feeding systems and the level of management were similar for all farms. Unless specified, machinery and equipment was purchased new, depreciated over ten years and replaced. Soils were uniform, well drained loams and the choice of the tillage and manure handling system was not limited by site-specific or environmental constraints. Corn grain was custom harvested and did not affect the progress of other field operations but a four cutting alfalfa harvest system was used which diverted labor from tillage and manure handling in mid-October. Government cost-sharing and tax effects were not considered.

5.1 COMPARISON OF MANURE HANDLING COST AND RESOURCE USE

Manure handling systems on Michigan dairy farms range from short-term storage with frequent hauling to long-term storage with irrigation or nurse tanker transport to fields located far from the herd. Frequent hauling is preferred by many producers because the direct costs are low, little specialized equipment is required and there are no concentrated labor demands. Long-term storage can allow for timely application, improve nutrient use and reduce runoff, but direct costs for specialized equipment and storage are high and labor needed for spreading may conflict with other field operations.

Manure moisture content greatly affected the amount of manure handled and had an impact on machinery selection and machinery, fuel, labor and total costs. Dilution of semi-solid manure at 13% DM to 9% DM for tanker transport increased the amount of material handled by 63% (Tables B.1-B.13) and more than doubled the mass of material handled when diluted to 6% DM for irrigation.

5.1.1 Nutrient Recovery

The slurry systems improved recovery of manurial nitrogen and led to a small reduction in commercial fertilizer purchased. The nutrient value of injected slurry was about $72/yr per cow plus replacements (Tables B.1-B.13). When incorporation was delayed, nitrogen losses continued for up to 15 days until all volatile N was lost. Volatile N losses reduced the nutrient value by about $3/cow-yr if the manure was delayed more than 15 days and $1.50/cow-yr with a three day delay in incorporation.

5.1.2 Manure Storage

Manure storage was the single greatest cost incurred in the change from short-term storage with daily hauling to long-term storage with slurry spreading. The lowest costs were for the slab/buckwall used with daily hauling. The annual ownership cost with this system was $3/cow-yr on each farm. Costs increased greatly with long-term slurry storage. When a dilute slurry (5%-7% DM) was irrigated, the required storage capacity increased about 33% and annual costs about 20%.

Table 5.1 Annual ownership costs for three manure storage systems.

	Ownership costs, $/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
Manure Storage					
slab/buckwall	3	3	3	3	3
clay-lined pit, slurry	51	32	28	25	20
clay-lined pit, liquid	58	39	34	31	27

5.1.3 Machinery

Machinery costs include implement ownership and repair and maintenance based on accumulated use. Tractor selection was based on power needed for economical forage harvest and feeding of the milking herd. Tractor and loader costs were based on proportional use but total costs changed little with use. Tractor ownership plus repair and maintenance costs were about $0.16/kW-hr ($0.12/hp-hr) and annual costs for tractors and loaders ranged from $210/cow-yr on the 60-cow farm to $120 on the 800-cow farm (Table 5.2). Annual costs increased to $233/cow-yr for the 60-cow farm when manure injection was used since a larger tractor was needed.

The V-tank spreader used for daily hauling was loaded directly from a push-off ramp so a special pump or loader was not required. Slurry hauling required a pit agitator/pump and slurry tankers for transport and spreading. When slurry injection was required, slurry injectors were added at an additional cost. The irrigation system required a pit agitator, a chopper pump to deliver a uniform material for pumping, a pressure pump, a traveling gun and 15 cm (6 in.) aluminum pipe for transport. When the pumping distance was greater than 1 km (0.62 mi) and auxiliary pump was used to provide sufficient pressure at the gun nozzle.

Table 5.2 Annual ownership costs for tractors, loaders and manure handling equipment.

	Ownership costs, $/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
Tractors and Loaders	210	156	152	141	120
Manure Handling Equipment					
spreader tanker, injection	74	37	39	27	24
spreader tanker, slurry	64	31	32	23	20
irrigation, liquid	89	41	26	23	22
V-tank, daily haul	63	31	20	13	13

The lowest cost for manure handling equipment was generally associated with daily hauling and the greatest with tanker injection. However, machinery costs for irrigation equipment varied greatly among farm sizes. Pumping capacity was fixed and this provided excess capacity and high costs on the 60 and 150-cow farms. Costs decreased on the larger farms where the pump capacity was better matched to the amount of material handled.

5.1.4 Fuel Use

Fuel use for manure handling varied with hauling method and pit agitation time. The most fuel was used for slurry injection and the least with V-tank spreading or slurry irrigation (Table 5.3). When the V-tank spreader was loaded directly from a push-off ramp, fuel use for hauling and spreading ranged from 18 L/cow-yr on the 60-cow farm to 41 L/cow-yr on the 800-cow farm. Bucket loading (front-end loader) increased fuel use about 7 L/cow-yr (2 gal/cow-yr). The slurry systems required tractors for both transport and agitation/pumping. Fuel use for pit agitation was about 10 L/cow-yr (2.6 gal/cow-yr) when the pit was agitated only during tanker filling and increased to about 12 L/cow-yr (3.2 gal/cow-yr) with continuous agitation during irrigation.

Fuel use for hauling and spreading with a V-tank spreader increased with herd size. Fuel use ranged from 18 to 21 L/cow-yr for herds of 60 to 250-cows as spreader capacity increased from 7,950 L (2,100 gal) to 10,975 L (2,900 gal). Larger tractors were used on the 400 and 800-cow farms but the spreader capacity remained the same as on the 250-cow farm since larger spreaders were not available. This increased fuel use. Hauling and spreading required 33 L/cow-yr (8.8 gal/cow-yr) on the 400-cow farm and 41 L/cow-yr (11.1 gal/cow-yr) on the 800-cow farm.

Table 5.3 Fuel use for manure loading, transport and spreading.

	Fuel use, L/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
injector tanker	48	43	48	61	73
spreader tanker	37	36	41	54	65
irrigation	22	25	27	43	48
V-tank w/push-off ramp	18	17	21	33	41
V-tank w/bucket loading	25	24	28	40	48

Manure irrigation was the most fuel efficient slurry spreading method. Fuel use nearly doubled on the 400 and 800-cow farms compared to the smaller farms since auxiliary pumps and tractors were added. Fuel use for irrigation ranged from 22 L/cow-yr (5.8 gal/cow-yr) for the 60-cow farm to 48 L/cow-yr (12.7 gal/cow-yr) for the 800-cow farm.

5.1.5 Labor

Labor for transport and spreading was influenced by spreading method and tanker loading and unloading rate. Tanker loading and unloading rates were influenced by the power available at the pump or spreader. Loading a V-tank spreader from a push-off ramp created no additional labor beyond that required for alley scraping. Transport and spreading in this manner required 1.4 h/cow-yr for the 60-cow herd and 1 h/cow-yr for the 150 and 250-cow herds where larger spreaders were used (Table 5.4). Labor for transport and spreading increased on the 400 (1.3 h/cow-yr) and 800-cow (1.6 h/cow-yr) farms since the hauling distance increased but the spreader capacity remained the same. Bucket (front-end loader) loading increased labor for manure handling about 0.75 h/cow-yr on each farm.

Even though the hauling distance was greater for the larger herds, labor efficiency (L hauled/min) for slurry hauling increased with the use of larger tankers and transfer pumps. The tanker loading rates ranged from 3,200 L/min (850 gpm) on the 60-cow farm to 4,150 L/min (1,100 gpm) on the 150 and 250-

cow farms and 5,100 L/min (1,350 gpm) on the 400 and 800-cow farms. Unloading rates ranged from 2,550 L/min (675 gpm) for the small tankers on the 60-cow farm to 3,400 L/min (900 gpm) on the larger farms. The tanker unloading rate was the same for both the tanker spreader and the tanker injector, but more time was needed for maintenance of the injector tankers. Tanker injection required about 10% more labor than tanker spreading. The unloading rate of the V-tank spreader was 2,840 L/min (750 gpm).

Tanker injection required the most labor of the manure handling methods. Labor decreased from 2.1 h/cow-yr for the 60-cow herd to 1.7 h/cow-yr for the 250-cow herd as tanker size increased from 8,325 L (2,200 gal) to 12,500 L (3,300 gal). Labor increased a small amount for the 400-cow (1.9 h/cow-yr) and 800-cow (2/h-cow-yr) farms as hauling distance increased but the use of larger tankers (15,150 L, 4,000 gal) helped reduce travel time. About 10% less labor was needed for tanker spreading than tanker injection since less time was needed for maintenance and repairs.

Table 5.4 Labor used for manure loading, transport and spreading.

	Labor, h/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
Hauling distance, km	**0.5**	**0.75**	**1.0**	**2.0**	**3.0**
injector tanker	2.1	1.9	1.7	1.8	2.2
spreader tanker	1.9	1.6	1.5	1.6	2.0
irrigation	1.2	1.1	1.0	1.4	1.9
V-tank w/push-off ramp	1.4	1.0	1.0	1.3	1.3
V-tank w/bucket loading	2.2	1.8	1.8	2.1	2.1

Manure irrigation required less labor than the other slurry systems. Irrigation required about 1.2 h/cow-yr on the 60-cow farm. An auxiliary pump was added on the larger farms if manure was pumped further than 1 km (0.62 mi). Labor increased to 1.4 h/cow-yr on the 400-cow farm since two people were required to tend the pump, auxiliary pump and traveler. Three people were needed to tend the two pressure pumps and two auxiliary pumps used on the 800-cow farm and labor needs increased to 1.9 h/cow-yr.

5.2 COMPARISON OF TILLAGE COST AND RESOURCE USE

Conventional tillage is favored on many livestock farms because of the ease with which both crop residue and manure can be incorporated and managed. Mulch-tillage is used on an increasing number of farms since machinery, fuel and labor costs can be reduced yet all manure handling options are available. Modified no-till can reduce fuel and labor costs and protect the soil from erosion but manure injection is not possible and nutrient loss to the environment may be greater.

5.2.1 Machinery

The highest ownership cost for tillage equipment was associated with conventional tillage and the lowest with mulch-till. Modified no-till equipment was slightly higher than mulch-till equipment (Table 5.5). The only tillage equipment used with the modified no-till system was a soil aerator and, if manure was irrigated, a rotary hoe. Lower costs for tillage equipment were largely offset by higher costs for planting equipment.

Table 5.5 Annual ownership costs for tractors, loaders and tillage equipment.

	Ownership costs, $/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
Tractors and Loaders	210	156	152	141	120
Tillage/Planting Equipment					
conventional	103	56	42	32	---
mulch-till	88	38	32	23	21
modified no-till	91	42	31	25	---

5.2.2 Fuel Use

The greatest fuel use for tillage and planting was associated with conventional tillage (Table 5.6). Fuel use ranged from 27 L/cow-yr (7.1 gal/cow-yr) on the 60-cow farm to 23 L/cow-yr (6.1 gal/cow-yr) on the 400-cow farm (Table 5.6). Mulch-tillage reduced fuel use about 30% compared to conventional tillage. Fuel use for mulch tillage ranged from 19 L (5 gal)/cow-yr on the 150-cow farm to 15 L (4 gal)/cow-yr on the 800-cow farm. The most fuel efficient system was modified no-till where fuel use dropped about 50% compared to conventional tillage. Fuel use for tillage and planting was about 13 L/cow-yr (3.7 gal/cow-yr) on most farms.

Table 5.6 Fuel use for tillage and planting.

	Fuel use, L/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
conventional	27	25	25	23	---
mulch-till	18	19	16	16	15
modified no-till	13	13	12	13	---

5.2.3 Labor

Labor decreased as tillage intensity decreased or larger tillage and planting equipment were used. The most labor was associated with conventional tillage on the small farms. Conventional tillage required about 2.0 h/cow-yr on the 60-cow farm but less than 1.0 h/cow-yr on the 400-cow farm (Table 5.7). Mulch-tillage reduced the labor needed for tillage and planting by about 35% compared to conventional tillage. Labor for mulch-tillage ranged from 1.2 h/cow on the 60-cow farm and 0.5 h/cow-yr on the 800-cow farm. Modified no-till generally required less than one-half of the labor needed for conventional tillage.

Table 5.7 Labor used for tillage and planting.

	Labor, h/cow-yr				
	60-cow	150-cow	250-cow	400-cow	800-cow
conventional	2.0	1.6	1.2	0.9	---
mulch-till	1.2	1.1	0.8	0.6	0.5
modified no-till	0.9	0.7	0.6	0.5	---

5.3 NET RETURN

The net return was calculated as the difference between the income from milk sales and the net cost of handling the manure, producing and harvesting the crops and feeding, milking and caring for the milking herd and young stock. The net return increased with herd size from 60 to 800 cows (Table 5.8). When mulch-tillage was used, 69% of the increase in net return gained by increasing herd size from 60 to 800 cows was obtained by increasing herd size from 60 to

150-cows. Increasing herd size to 250-cows provided 81% and 400 cows provided 90% of the net return available to the 800-cow herd.

Table 5.8 Net return for three tillage and four manure spreading systems.

	Net Return, $/cow-yr			
	Tank Injector	Tank Spreader	Irrigation	V-Tank
60-cow				
conventional	-342	-313	-316	-246
mulch-till	-303	-278	-281	-213
modified no-till	---	-298	-301	-220
150-cow				
conventional	225	245	253	303
mulch-till	251	269	278	327
modified no-till	---	264	265	321
250-cow				
conventional	334	346	355	389
mulch-till	354	364	374	410
modified no-till	---	357	363	406
400-cow				
conventional	408	421	437	462
mulch-till	425	438	453	477
modified no-till	---	428	440	470
800-cow				
mulch-till	502	518	539	558

Mulch-till provided the greatest return among tillage systems. The annual cost of tillage equipment for modified no-till was similar to mulch-till (Table 5.5), but fuel (Table 5.6) and labor (Table 5.7) costs were lower for modified no-till. However, these savings were offset by higher costs for seed, fertilizer, herbicides and insecticides (Table 4.2). Seed and chemical costs were $32/ha ($13/ac) higher for establishment year alfalfa and $17/ha ($7/ac) for corn following alfalfa in the modified no-till system. Fertilizer costs about $3.00/cow-yr higher with the no-till system where manure was not incorporated. Mulch-till

till increased net return about $19/cow-yr compared to modified no-till for the 60-cow herd but the advantage was only about $10/cow-yr for the 400-cow herd.

Across tillage systems the highest net return was associated with short-term manure storage and frequent hauling and the lowest with long-term storage and tanker injection. Compared to slurry injection, slurry spreading increased net return about $10/cow-yr for farms of 150 cows or more and increased net return even more ($25/cow-yr) for the 60-cow farm. Compared to slurry injection, irrigation improved net returns $18/cow-yr on the 60-cow farm and $37/cow-yr on the 800-cow farm.

The greatest net return among manure hauling systems was associated with short-term storage and frequent hauling with a V-tank spreader if the manure nutrient value is included. The advantage for daily hauling over slurry injection ranged from $96/cow-yr on the 60-cow farm with conventional tillage to $56/cow-yr with mulch-tillage on the 800-cow farm. Most of the difference in net return between long-term and short-term storage systems was due to the high cost of manure storage (Table 5.1). If the nutrient value ($72/cow-yr) of the manure was not included there was little difference in net return between daily hauling and slurry systems with long-term storage.

5.4 EFFECT OF LABOR SCHEDULE ON SYSTEM PERFORMANCE

The timeliness of tillage and planting is influenced by the number of simultaneous operations and the type of tillage and manure handling used. On small farms, one person may have responsibility for all field work plus management and care of the livestock. On larger farms, one or more workers may devote all their attention to field work or their time may be divided between field and livestock duties. More labor and power is usually available on larger farms so manure hauling and tillage may be able to progress simultaneously. The expected completion dates (50% probability) for major field operations for representative farms with varying labor schedules are listed in Tables 5.9-5.14.

5.4.1 60-Cow Farm: One Operation, Tillage and Manure Handling in Series.

One person was available six hours per day for all field operations on the 60-cow farm. Fall tillage and spreading began after corn silage was harvested in late September but was delayed by alfalfa harvest in mid-October. Corn grain was custom harvested and did not require on-farm labor. Spreading from long-term storage delayed both the start and finish of fall tillage. Conventional tillage was complete by November 2 when manure was hauled daily but was not finished until about nine days later with tanker injection (Table 5.9).

The longest delays in spring tillage and manure spreading were associated with conventional tillage and tanker injection. Spring spreading began April 9 with conventional and mulch-tillage on the 60-cow farm and a day later with modified no-till. Manure irrigation was finished within a few days but tanker injection required more than two weeks. Spring tillage was finished by the end of the first week in May in most years on the 60-cow farm.

Corn planting began May 1 and was finished by May 5 with each tillage system if manure was hauled daily. Slurry injection delayed planting five to eight days. The latest corn planting was associated with conventional tillage but neither tillage nor manure hauling had a strong adverse effect on timeliness. Tanker injection caused the greatest variability in corn planting on the 60-cow farm. Planting with conventional tillage was finished after May 20 four times following tanker injection and three times following tanker spreading but was always finished by May 20 with daily hauling or irrigation. Delaying planting with tanker injection increased feed costs about $4/cow-yr compared to daily hauling of manure.

5.4.2 Effect of Hours Worked on System Performance, 60-cow Farm

The effect of hours worked on system performance was demonstrated by comparing timeliness with both six and eight hour days spent on field operations. Increasing the length of the workday improved the ability to complete field operations in a timely fashion.

Since the equipment used on the 60-cow farm had sufficient capacity to allow field work to be completed with little delay with all tillage and manure hauling methods, there was little economic benefit in increasing the length of the workday. Increasing the length of work day to eight hours had the greatest impact with tanker injection in a conventional tillage system. Compared to the six hour day, fall spreading by tanker injection was completed three days sooner

Table 5.9 Predicted dates (50% probability) to begin and end major field operations for a 60-cow dairy in central Michigan: one implement working six hours per day, field operations in series.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/23	10/20	9/28	11/11	4/9	4/24	4/25	5/7	5/8	5/12
	(3.7) [1]	(9.7)	(4.1)	(21.8)	(6.8)	(9.1)	(9.3)	(9.9)	(8.7)	(8.9)
				[3] [2]						[4]
Slurry tankers	9/22	10/17	9/26	11/8	4/9	4/21	4/23	5/4	5/6	5/11
	(3.5)	(7.1)	(3.8)	(19.7)	(7.0)	(8.8)	(8.5)	(8.8)	(7.2)	(8.2)
				[3]						[3]
Liquid irrigation	9/22	10/12	9/24	11/4	4/9	4/12	4/15	4/29	5/2	5/6
	(3.5)	(4.9)	(3.4)	(20.4)	(7.0)	(7.3)	(6.0)	(5.5)	(3.4)	(4.6)
				[3]						[0]
Semi-solid, daily haul	--	--	9/23	11/2	--	--	4/13	4/27	5/1	5/5
			(3.7)	(17.7)			(3.3)	(3.9)	(1.9)	(3.5)
				[3]						[0]
Mulch-till										
Slurry injection	9/23	10/19	10/1	11/3	4/9	4/25	4/28	5/3	5/5	5/10
	(3.6)	(9.9)	(6.8)	(20.6)	(6.9)	(9.4)	(7.5)	(7.7)	(5.7)	(7.6)
				[3]						[3]
Slurry tankers	9/23	10/16	9/28	11/1	4/9	4/22	4/26	5/1	5/3	5/9
	(3.5)	(6.9)	(4.1)	(17.9)	(7.0)	(8.7)	(6.5)	(6.3)	(4.2)	(7.3)
				[2]						[3]
Liquid irrigation	9/23	10/11	9/24	10/22	4/9	4/13	4/22	4/28	5/1	5/5
	(3.5)	(4.8)	(3.5)	(10.3)	(7.0)	(7.3)	(3.3)	(4.0)	(1.9)	(2.8)
				[0]						[0]
Daily haul	--	--	9/24	10/19	--	--	4/21	4/27	5/1	5/5
			(3.4)	(9.4)			(2.0)	(3.9)	(1.5)	(2.6)
				[0]						[0]
Modified no-till										
Slurry tankers	9/22	10/17	9/26	10/31	4/10	4/23	--	--	5/3	5/7
	(3.5)	(7.1)	(3.8)	(17.9)	(7.0)	(8.9)			(3.3)	(5.3)
				[2]						[2]
Liquid irrigation	9/22	10/11	9/24	10/19	4/10	4/13	4/19	4/22	5/2	5/5
	(3.5)	(4.9)	(3.4)	(9.6)	(7.0)	(7.5)	(4.8)	(6.3)	(4.0)	(4.2)
				[0]						[1]
Daily haul	--	--	9/23	10/17	--	--	--	--	5/2	5/5
			(3.7)	(9.7)					(3.9)	(4.1)
				[0]						[1]

with the longer workday (Table 5.10). Moldboard plowing was finished about a week earlier and chisel plowing two to three days earlier than with a six hour

[1] ( ) indicates standard deviation from the mean.

[2] [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

Table 5.10. Predicted dates (50% probability) to begin and end major field operations for a 60-cow dairy in central Michigan: one implement working eight hours per day, field operations in series.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/23	10/18	9/29	11/5	4/9	4/21	4/22	5/1	5/4	5/8
	(3.7) [1]	(9.9)	(4.1)	(20.3)	(6.8)	(9.0)	(8.3)	(7.8)	(5.2)	(6.8)
				[3] [2]						[2]
Slurry tankers	9/22	10/15	9/25	11/3	4/9	4/18	4/20	4/30	5/3	5/6
	(3.5)	(6.9)	(3.5)	(17.7)	(7.0)	(8.7)	(7.7)	(7.0)	(4.4)	(5.0)
				[3]						[1]
Liquid irrigation	9/22	10/12	9/24	10/24	4/9	4/10	4/14	4/27	5/1	5/4
	(3.5)	(4.9)	(3.4)	(9.9)	(7.0)	(7.0)	(5.0)	(4.7)	(2.2)	(3.4)
				[1]						[0]
Semi-solid,	--	--	9/23	10/24	--	--	4/13	4/26	5/1	5/4
daily haul			(3.7)	(9.6)			(3.3)	(4.0)	(1.6)	(2.8)
				[0]						[0]
Mulch-till										
Injection	9/23	10/17	9/28	11/2	4/9	4/22	4/26	4/29	5/3	5/6
	(3.7)	(9.9)	(4.1)	(10.6)	(6.9)	(9.1)	(6.0)	(6.5)	(3.7)	(4.6)
				[1]						[0]
Tankers	9/23	10/14	9/27	10/23	4/9	4/19	4/24	4/28	5/2	5/4
	(3.5)	(6.6)	(4.0)	(10.0)	(7.0)	(9.1)	(5.1)	(5.4)	(2.6)	(3.5)
				[0]						[0]
Irrigation	9/23	10/11	9/24	10/18	4/9	4/11	4/21	4/26	5/1	5/4
	(3.5)	(4.8)	(3.5)	(9.7)	(7.0)	(7.1)	(2.0)	(4.0)	(1.6)	(2.0)
				[0]						[0]
Daily haul	--	--	9/24	10/17	--	--	4/21	4/25	5/1	5/3
			(3.6)	(9.7)			(2.0)	(3.3)	(1.4)	(1.8)
				[0]						[0]
Modified no-till										
Tankers	9/22	10/15	9/26	10/22	4/10	4/20	--	--	5/1	5/5
	(3.5)	(6.9)	(3.9)	(10.2)	(7.0)	(8.8)			(4.1)	(4.7)
				[0]						[1]
Irrigation	9/22	10/11	9/24	10/18	4/10	4/12	4/18	4/20	5/2	5/4
	(3.5)	(4.9)	(3.4)	(9.9)	(7.0)	(7.5)	(3.4)	(6.0)	(1.4)	(4.2)
				[0]						[1]
Daily haul	--	--	9/24	10/18	--	--	--	--	5/1	5/4
			(3.4)	(9.6)					(1.4)	(3.9)
				[0]						[1]

day. When manure was hauled daily, fall tillage was rarely delayed beyond the end of November regardless of the tillage system used.

[1] ( ) indicates standard deviation from the mean.

[2] [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

Spring tillage and planting were not greatly affected little by the longer work day if manure was hauled daily, but corn was planted about four days sooner when slurry injection was used. Compared to a six hour work day, feed costs were reduced about $2/cow-yr with an eight hour day with conventional tillage and slurry injection.

5.4.3 150-Cow Farm: One Operation, Tillage and Manure Handling in Series.

One person was available ten hours per day for tillage, planting and manure handling on the 150-cow farm. Manure handling, tillage and planting progressed in series. Slurry injection and tanker spreading delayed planting and led to high timeliness costs.

Fall tillage and spreading began in late September after corn silage harvest (Table 5.11). Manure irrigation was finished in early October but slurry injection was not finished until the end of October. Fall tillage began in late September and moldboard plowing was finished by the end of October when manure was hauled daily. When slurry injection was used tillage began in early November and was not finished until early December. Chisel plowing was finished about two weeks sooner than moldboard plowing.

The longest delays in spring tillage and spreading were associated with conventional tillage and tanker injection. Spring spreading began about April 10 and manure irrigation was finished about a week later. Slurry injection was not finished until the first week of May. Spring tillage was finished by the end of

Table 5.11 Predicted dates (50% probability) to begin and end major field operations for a 150-cow dairy in central Michigan: one implement working ten hours per day, field operations in series.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/28	10/28	11/3	12/5	4/9	5/6	5/7	5/16	5/16	5/24
	(3.8) [1]	(19.5)	(26.5)	(26.0)	(6.8)	(11.2)	(11.1)	(10.7)	(10.2)	(10.2)
				[12] [2]						[15]
Slurry tankers	9/27	10/16	10/20	11/26	4/9	4/29	5/1	5/12	5/13	5/19
	(3.6)	(11.3)	(17.2)	(26.9)	(7.0)	(9.4)	(10.4)	(10.1)	(9.4)	(9.6)
				[9]						[13]
Liquid irrigation	9/27	10/7	10/7	11/7	4/9	4/17	4/19	5/3	5/4	5/12
	(3.6)	(6.3)	(9.5)	(24.4)	(7.0)	(8.5)	(7.2)	(7.0)	(5.5)	(7.7)
				[4]						[4]
Semi-solid, daily haul	--	--	9/28	10/30	--	--	4/13	4/29	5/1	5/9
			(3.8)	(25.2)			(3.3)	(3.8)	(2.1)	(4.5)
				[3]						[1]
Mulch-till										
Injection	9/28	10/28	11/3	11/22	4/9	5/7	5/8	5/15	5/15	5/23
	(3.8)	(19.5)	(26.5)	(27.9)	(6.9)	(11.6)	(11.3)	(11.0)	(10.5)	(10.4)
				[9]						[15]
Tankers	9/27	10/16	10/20	11/9	4/9	5/1	5/3	5/11	5/11	5/18
	(3.6)	(11.3)	(17.2)	(23.3)	(7.0)	(10.1)	(9.3)	(10.0)	(9.6)	(9.3)
				[4]						[10]
Irrigation	9/27	10/7	10/7	10/22	4/9	4/18	4/24	5/2	5/4	5/12
	(3.6)	(6.3)	(9.5)	(18.6)	(7.0)	(9.0)	(4.8)	(5.5)	(4.2)	(7.2)
				[2]						[3]
Daily haul	--	--	9/28	10/17	--	--	4/21	4/29	5/2	5/10
			(3.8)	(17.4)			(2.0)	(3.8)	(2.1)	(4.9)
				[1]						[0]
Modified no-till										
Tankers	9/27	10/16	10/20	11/1	4/10	5/2	--	--	5/9	5/15
	(3.6)	(11.3)	(17.2)	(23.6)	(7.0)	(10.7)			(9.1)	(9.3)
				[4]						[7]
Irrigation	9/27	10/7	10/7	11/16	4/10	4/19	4/24	4/30	5/3	5/11
	(3.6)	(6.3)	(9.6)	(17.7)	(7.0)	(9.0)	(4.9)	(5.5)	(4.5)	(7.1)
				[1]						[4]
Daily haul	--	--	9/28	10/9	--	--	--	--	5/2	5/8
			(3.8)	(9.1)					(3.7)	(4.6)
				[0]						[1]

[1] ( ) indicates standard deviation from the mean.

[2] [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

April when manure was hauled daily but was delayed until the middle of May by slurry injection. Corn was planted by May 10 when manure was hauled daily but was not planted until late May with manure injectionTanker injection caused the greatest variability in corn planting on the 150-cow farm. Delayed planting decreased the amount of grain produced and the quality of feeds fed, increased feed costs and decreased net return (Tables B.4-B.6). Planting delays with conventional tillage increased feed costs $24/cow-yr with slurry injection and $15/cow-yr with tanker spreading.

5.4.4 250-Cow Farm: Two Operations, Tillage and Manure Handling in Series.

Two manure tankers were used for slurry hauling on the 250-cow farm. Two workers were available ten hours per day and manure hauling and tillage were in series; manure storage was emptied before fall tillage began. If manure was hauled daily, tillage began as soon as corn silage was harvested.

Delaying fall tillage five to eight days in late September delayed the finish as much as two weeks since suitable days drop off rapidly after the end of October (Table 5.13). If manure was hauled daily moldboard plowing was finished by early November but slurry injection delayed plowing as much as three weeks. Chisel plowing was finished one or two weeks sooner and soil aeration two or three weeks sooner than moldboard plowing. The longest delay with each tillage system was associated with tanker injection.

Table 5.12 Predicted dates (50% probability) to begin and end major field operations for a 250-cow dairy in central Michigan: two implement working ten hours per day, manure application and tillage in series.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/23	10/17	10/2	11/20	4/9	4/25	4/26	5/12	5/12	5/18
	(3.7) [3]	(17.9)	(8.8)	(28.1)	(6.8)	(9.5)	(9.5)	(10.0)	(9.5)	(9.8)
				[8] [4]						[10]
Slurry tankers	9/22	10/11	9/28	11/13	4/9	4/21	4/24	5/10	5/10	5/15
	(3.5)	(10.5)	(3.7)	(27.2)	(7.0)	(8.8)	(9.0)	(9.6)	(9.2)	(9.2)
				[6]						[8]
Liquid irrigation	9/22	10/11	9/27	11/9	4/9	4/20	4/23	5/9	5/9	5/14
	(3.5)	(9.9)	(4.0)	(24.2)	(7.0)	(8.7)	(8.5)	(9.6)	(9.1)	(9.0)
				[4]						[6]
Semi-solid, daily haul	--	--	9/23	10/29	--	--	4/13	5/1	5/3	5/9
			(3.7)	(20.9)			(3.3)	(4.7)	(3.4)	(5.6)
				[2]						[2]
Mulch-till										
Slurry injection	9/23	10/17	10/2	11/5	4/9	4/27	4/29	5/8	5/9	5/15
	(3.7)	(17.8)	(8.8)	(23.2)	(6.9)	(9.7)	(7.6)	(9.9)	(9.1)	(9.5)
				[3]						[7]
Slurry tankers	9/22	10/11	9/28	10/27	4/9	4/22	4/27	5/6	5/7	5/13
	(3.5)	(10.5)	(4.7)	(17.4)	(7.0)	(8.7)	(6.8)	(9.0)	(8.2)	(8.5)
				[2]						[5]
Liquid irrigation	9/22	10/11	9/27	10/27	4/9	4/20	4/26	5/5	5/6	5/13
	(3.5)	(10.0)	(4.0)	(17.1)	(7.0)	(8.7)	(6.5)	(8.3)	(7.3)	(8.2)
				[2]						[5]
Daily haul	--	--	9/23	10/20	--	--	4/21	5/1	5/2	5/8
			(3.7)	(18.3)			(2.0)	(3.8)	(2.5)	(4.3)
				[2]						[0]
Modified no-till										
Slurry tankers	9/22	10/11	9/28	10/22	4/10	4/23	--	--	5/5	5/11
	(3.5)	(10.5)	(4.7)	(17.5)	(7.0)	(9.0)			(5.3)	(7.6)
				[1]						[4]
Liquid irrigation	9/22	10/11	9/27	10/22	4/10	4/21	4/27	5/3	5/6	5/12
	(3.5)	(10.0)	(4.0)	(17.5)	(7.0)	(8.7)	(6.4)	(6.9)	(6.0)	(7.9)
				[1]						[4]
Daily haul	--	--	9/23	10/16	--	--	--	--	5/2	5/7
			(3.7)	(17.6)					(3.9)	(4.7)
				[1]						[1]

[3] ( ) indicates standard deviation from the mean.

[4] [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

The longest delay in spring tillage was associated with conventional tillage and within tillage systems, with tanker injection. Spring spreading began by April 10. Slurry irrigation was finished by April 20 and tanker injection a few days later. Conventional spring tillage began about two weeks sooner with daily manure hauling than with tanker injection. Spring tillage was finished by early May with daily hauling but was delayed as much as twelve days by slurry injection.

Corn was usually planted by May 10 (50% probability) with daily hauling but slurry injection delayed planting a week or more. Manure irrigation caused a small delay in planting but on most farms, the irrigation system would have been operated more hours per day and on days when the soil was dry enough to prevent runoff but too wet for tanker traffic. Under such management irrigation would rarely delay planting. Compared to daily hauling, feed costs increased $11 to $13/cow-yr with conventional tillage, $8 to $12/cow-yr with mulch-tillage and $3 to $5/cow-yr with modified no-till (Tables B.9-B.11).

5.4.5 250-Cow Farm: Three Operations, Parallel Tillage and Manure Handling.

An alternative labor schedule using three workers eight hours per day was used on the 250-cow farm. This allowed tillage to begin at the same time as slurry spreading. Other than a small advantage with the longer workday, there was little difference in fall spreading with the two labor schedules since the same equipment was used (Table 5.13). However, since fall tillage began at the same

Table 5.13 Predicted dates (50% probability) to begin and end major field operations for a 250-cow dairy in central Michigan: three implements working eight hours per day, parallel manure application and tillage.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/23	10/20	9/23	11/4	4/9	4/28	4/13	5/3	5/4	5/12
	(3.7) [1]	(18.5)	(3.7)	(19.5)	(6.8)	(9.6)	(3.3)	(6.9)	(5.2)	(7.4)
				[2] [2]						[4]
Slurry tankers	9/22	10/14	9/23	11/4	4/9	4/25	4/13	5/1	5/3	5/10
	(3.5)	(12.0)	(3.7)	(19.4)	(7.0)	(9.4)	(3.3)	(6.4)	(3.9)	(6.4)
				[2]						[3]
Liquid irrigation	9/22	10/13	9/23	11/4	4/9	4/23	4/13	4/29	5/1	5/8
	(3.5)	(11.5)	(3.7)	(19.4)	(7.0)	(9.0)	(3.3)	(4.4)	(2.1)	(4.6)
				[2]						[3]
Semi-solid,	--	--	9/23	11/4	--	--	4/13	4/27	5/1	5/8
daily haul			(3.7)	(19.4)			(3.3)	(3.7)	(1.3)	(4.0)
				[2]						[1]
Mulch-till										
Injection	9/23	10/19	9/23	10/25	4/9	4/30	4/21	5/1	5/2	5/11
	(3.7)	(18.7)	(3.7)	(21.2)	(6.9)	(10.4)	(2.0)	(4.4)	(2.9)	(6.0)
				[2]						[3]
Tankers	9/22	10/14	9/23	10/25	4/9	4/27	4/21	5/1	5/2	5/10
	(3.5)	(12.0)	(3.7)	(21.1)	(7.0)	(9.5)	(2.0)	(4.6)	(2.8)	(6.0)
				[2]						[2]
Irrigation	9/22	10/14	9/23	10/25	4/9	4/23	4/21	4/29	5/1	5/9
	(3.5)	(11.5)	(3.7)	(21.1)	(7.0)	(9.2)	(2.0)	(4.2)	(1.7)	(4.3)
				[2]						[0]
Daily haul	--	--	9/23	10/25	--	--	4/21	4/27	5/1	5/8
			(3.7)	(21.1)			(2.0)	(3.9)	(1.3)	(3.9)
				[2]						[0]
Modified no-till										
Tankers	9/22	10/14	9/23	10/18	4/10	4/27	--	--	5/1	5/8
	(3.5)	(12.0)	(3.7)	(17.6)	(7.0)	(9.4)			(3.9)	(4.7)
				[1]						[1]
Irrigation	9/22	10/13	9/23	10/21	4/10	4/24	4/21	4/26	5/2	5/8
	(3.5)	(11.5)	(3.7)	(17.6)	(7.0)	(9.2)	(2.0)	(4.3)	(3.9)	(4.7)
				[1]						[1]
Daily haul	--	--	9/23	10/18	--	--	--	--	5/2	5/8
			(3.7)	(17.6)					(3.9)	(4.7)
				[1]						[1]

1 ( ) indicates standard deviation from the mean.

2 [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

time as slurry hauling, there was little difference in the completion of fall tillage whether manure was hauled daily (November 5) or injected (November 8). Chisel plowing was finished about one week and aeration two weeks sooner than moldboard plowing.

Spring slurry injection was finished five to seven days later than slurry irrigation. Spring tillage was finished by the end of April when manure was hauled daily and four to six days later with tanker injection. Delaying spring tillage with tanker injection delayed corn planting. Corn was planted by May 8 when manure was hauled daily. Tanker injection delayed corn planting three to four days.

5.4.6 400-Cow Farm: Three Operations, Parallel Tillage and Manure Handling.

Three workers were available ten hours per day on the 400-cow farm. This allowed parallel tillage and manure hauling. Compared to the 250-cow farm a longer workday, larger slurry tankers and tillage equipment were used (Table 4.8). When using mulch-tillage, fall tillage was finished about two weeks sooner if manure was hauled daily (October 22) than if injected (Table 5.14). Slurry injection delayed spring tillage more than one week. Corn was usually planted by May 10 with daily hauling but was delayed about six days with tanker injection. Compared to daily manure hauling on the 400-cow farm, feed related costs increased $4/cow-yr with tanker spreading, $6/cow-yr with irrigation and $9/cow-yr with tanker injection (Table B.11).

Table 5.14 Predicted dates (50% probability) to begin and end major field operations for a 400-cow dairy in central Michigan: three implements working ten hours per day, parallel manure application and tillage.

	Fall Spreading		Fall Tillage		Spring Spreading		Spring Tillage		Corn Planting	
	Begin	End	Begin	End	Begin	End	Begin	End	Begin	End
Conventional										
Slurry injection	9/26 (3.8) [3]	10/27 (18.3)	9/26 (3.8)	11/15 (23.6) [5] [4]	4/9 (6.8)	5/7 (11.1)	4/13 (3.3)	5/1 (4.7)	5/3 (3.4)	5/11 (6.6) [4][2]
Slurry tankers	9/26 (3.5)	10/19 (12.5)	9/26 (3.8)	11/15 (23.6) [5]	4/9 (7.0)	5/2 (10.4)	4/13 (3.3)	5/2 (5.2)	5/3 (3.8)	5/11 (6.7) [4]
Liquid irrigation	9/26 (3.5)	10/15 (11.6)	9/26 (3.8)	11/15 (23.6) [5]	4/9 (7.0)	4/27 (9.3)	4/13 (3.3)	4/28 (3.9)	5/1 (1.9)	5/8 (4.5) [1]
Semi-solid, daily haul	--	--	9/26 (3.8)	11/15 (23.6) [2]	--	--	4/13 (3.3)	4/27 (3.6)	5/1 (1.3)	5/8 (3.9) [1]
Mulch-till										
Injection	9/26 (3.8)	10/27 (18.3)	9/26 (3.8)	10/31 (18.6) [2]	4/9 (6.9)	5/8 (11.6)	4/21 (2.0)	5/2 (4.1)	5/3 (3.0)	5/11 (5.2) [0]
Tankers	9/26 (3.5)	10/19 (12.5)	9/26 (3.8)	11/4 (21.1) [2]	4/9 (7.0)	5/4 (10.6)	4/21 (2.0)	5/1 (4.1)	5/3 (3.0)	5/10 (5.1) [0]
Irrigation	9/26 (3.5)	10/15 (11.6)	9/26 (3.8)	10/31 (18.6) [2]	4/9 (7.0)	4/28 (9.3)	4/21 (2.0)	4/29 (3.9)	5/1 (1.5)	5/8 (3.9) [0]
Daily haul	--	--	9/26 (3.8)	10/31 (18.6) [2]	--	--	4/21 (2.0)	4/27 (3.9)	5/1 (1.3)	5/8 (3.9) [0]
Modified no-till										
Tankers	9/26 (3.5)	10/19 (12.5)	9/26 (3.8)	10/20 (12.3) [0]	4/10 (7.0)	5/5 (11.4)	--	--	5/2 (3.8)	5/9 (4.8) [1]
Irrigation	9/26 (3.5)	10/15 (11.6)	9/26 (3.8)	10/20 (12.3) [0]	4/10 (7.0)	4/29 (9.5)	4/21 (2.0)	4/28 (4.0)	5/2 (3.8)	5/9 (4.8) [1]
Daily haul	--	--	9/26 (3.8)	10/20 (12.3) [0]	--	--	--	--	5/2 (3.7)	5/8 (4.6) [1]

[3] ( ) indicates standard deviation from the mean.

[4] [ ] indicates number of years in 26 when fall tillage was delayed beyond November 30 or corn planting beyond May 20.

5.5 APPLICABILITY OF THE SIMULATION RESULTS

Farmers considering expansion or seeking to improve their farming system should evaluate both tillage and manure handling systems. Compared to conventional tillage, mulch-tillage can reduce machinery costs, fuel use and labor and improve the timeliness of field operations. Modified no-till can further decrease fuel and labor costs but those savings may be offset by higher costs for seed, herbicides, insecticides and fertilizer. Slurry injection and tanker spreading may delay tillage and planting. When using these systems, adequate labor, power and equipment should be available to allow parallel tillage and manure spreading operations. Daily hauling can improve timeliness and simplify labor scheduling on most farms.

The profitability of manure handling systems depends upon the ability to recycle manure nutrient for crop production and reduce commercial fertilizer costs. Accounting for these nutrients is easier when spreading stored manure than when spreading daily. When manure is hauled daily, nutrient concentration and uniformity of distribution is highly variable both within and between fields. Fields close to the barn often receive heavier applications than more remote locations. Coarse textured soils receive manure when the soil is wet, fine texture soils when the soil is dry. And during the growing season, some fields are left uncropped for the purpose of manure disposal. If the value of the spread manure

($72/cow-yr) is reduced to allow for inefficient use, the net return with daily hauling is be similar to slurry systems.

Cost and labor requirements are important but environmental constraints, together with governmental regulations, will strongly influence the selection of tillage and manure handling systems in the future. Environmental risks are farm and field specific. Manure spread on frozen or snow covered, sloping fields adjacent to surface waters may threaten water quality. But the risk is not great if fields are nearly level and conservation tillage is combined with vegetative buffer strips or other erosion control structures to prevent runoff. Manure injection may be the best way to minimize odor and runoff, but it may not be the best choice for coarse textured soil with a high water tables since deep placement may facilitate leaching of nitrogen to groundwater. Manure irrigation is cost effective and labor efficient but over-application, runoff, wind drift and odor transport are potential problems. Irrigation is best suited to level or gently sloping fields in sparsely populated areas.

6. CONCLUSIONS

The expanded DAFOSYM model provides a flexible and useful tool for comparing the long-term performance and economics of tillage and manure handling systems on dairy farms.

1. The highest machinery, fuel, labor and timeliness costs for manure hauling were associated with slurry injection and the lowest with daily V-tank hauling if the spreader was loaded from a push-off ramp during alley scraping. If bucket loading of the spreader was used, costs were similar to the slurry hauling systems.
2. The lowest fuel, labor and timeliness costs for slurry manure systems were associated with irrigation.
3. The greatest net return among manure hauling systems was associated with short-term storage and daily hauling if manure nutrients were recovered for crop growth. Irrigation provided the greatest return and slurry injection the lowest return among slurry systems. If manure nutrients were not recovered and used for crop growth, the net return with daily hauling was similar to the slurry hauling systems.
4. The highest machinery, fuel, labor and timeliness costs for tillage and planting were associated with moldboard plowing and conventional seedbed preparation. Compared to conventional tillage, mulch-tillage reduced machinery, fuel and labor costs about 30%. Machinery costs for

the modified no-till system were similar to mulch-tillage, but fuel and labor costs were further reduced to about 50% of that needed for conventional tillage.

5. The greatest net return among tillage systems was associated with mulch-tillage. Modified no-till provided a higher return than conventional tillage, but compared to mulch-tillage, savings in fuel and labor were offset by higher costs for seed, fertilizer, herbicides and insecticides.

6. Net return increased with herd size from 60 to 800 cows with all tillage/manure systems. Most of the increase in net return (69%) was gained as herd size increased from 60 to 150 cows. Increasing herd size to 250 cows provided 81% and 400 cows, 90% of the net return earned by the 800-cow farm.

7. The number of simultaneous field operations and length of workday influenced system cost and performance. The highest timeliness costs were associated with tanker injection and conventional tillage. The lowest timeliness costs were associated manure irrigation or daily manure hauling.

7. RECOMMENDATIONS

The following recommendation is made with respect to the need for future research.

1. Simulation models such as DAFOSYM must be further refined and expanded to allow additional crops such as wheat and soybeans in the crop mix. These crops provide flexibility in timing of manure application and efficiency of nutrient utilization and may help determine the best machinery and management alternatives for individual farms.

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APPENDICES

APPENDIX A

Subroutine SUITDAY

```
C*********************************************************************
      SUBROUTINE SUITDAY
C*********************************************************************
C  DETERMINES IF A GIVEN DAY IS SUITABLE FOR FIELD WORK.  BASED
C  ON CERES-MAIZE BY JONES AND KINRY, 1986
C
C     SOIL(S,3)=unitless, bare soil albedo
C     SOIL(S,4)=mm/d, upper limit of stage 1 soil evap.
C     SOIL(S,5)=g/cc, soil bulk density
C     SOIL(S,6)=%, organic carbon
C     SOIL(S,7)=constant
C     SOIL(S,8)=%, silt content
C     SOIL(S,9)=%, clay content
C     SOIL(S,10)=%, sand content
C     SOIL(S,11)=SCS runoff curve number
C     SOIL(S,12)=whole profile drainage rate coefficient
C     LL=lower limit of plant extractable water, cm/cm
C     DUL=field capacity extractable water, cm/cm
C     SAT=saturated soil water, cm/cm
C     PO=%, soil porosity
C     XZ=density correction factor
C     BDM=g/cc, maximum bulk density
C     DLAYR=cm, depth of soil layers
C     NLAYR=number of soil layers to simulate
C     ES=actual soil evap., mm/d
C     EOS=potential soil evaporation, mm/d
C     ESW=cm/cm, extractable soil water
C     RC=residue cover, %
C     SWR=relative plant ext. soil water in layer
C     FLUX=saturated moisture flow between layers
C     DRAIN=cm/d, drainage rate from a layer
C     WINF=cm, precip that infiltrates
C     THET1=soil water above LL for upper layer, cm/cm
C     THET2=soil water above LL for lower layer, cm/cm
C     DBAR=avg soil water diffusivity
C     FLOW=unsat. flow, cm
C
      INTEGER S,ND(12)
C      +,IWGT5(45)
```

```
      REAL LL,DLAYR(4),SW(4)
C      +,SDP(26,18),SDPMS(3,18),PROB(18)
      INCLUDE 'GENERAL.BLK'
      INCLUDE 'TILL.BLK'
      INCLUDE 'MANURE.BLK'
      INCLUDE 'OPER.BLK'

      DATA DLAYR /3.,4.6,7.6,100./,NLAYR /4/
      DATA ND /31,28,31,30,31,30,31,31,30,31,30,31/
C
C  DETERMINE SOIL WATER HOLDING CAPACITY
      S=ISOIL
      PO=1-SOIL(S,5)/2.65
      XZ=SOIL(S,6)*0.0172
      BDM=(1-XZ)/(1/SOIL(S,5)-XZ/0.224)
      IF(SOIL(S,10).GT.75) THEN
        W1=0.19-0.0017*SOIL(S,10)
        W2=0.429-0.00388*SOIL(S,10)
      ELSEIF(SOIL(S,8).GT.70) THEN
        W1=0.16
        W2=0.1079+0.000504*SOIL(S,8)
      ELSE
        W1=0.0542+0.00409*SOIL(S,9)
        W2=0.1079+0.000504*SOIL(S,8)
      ENDIF
      LL=W1*(1.-XZ)*(1.+BDM-SOIL(S,5))+0.23*XZ
      DUL=LL+W2*(1.-XZ)-(BDM-SOIL(S,5))*0.2+0.55*XZ
      SAT=SOIL(S,7)*(PO-DUL)+DUL
      DO J=1,NLAYR
        SW(J)=SAT
      ENDDO
      SWEF=0.9-0.00038*(DLAYR(1)-30.)**2
C
C  DETERMINE SPRING THAW DATE
      DD=0.
      TMAX=0.
      DO I=60,110
        TAV=AMAX1(0.,(WTHR(I,3)+WTHR(I,4))/2.)
        IF(TAV.LE.0) DD=0.
        TMAX=AMAX1(TMAX,TAV)
        IF(TMAX.GT.7) THEN
          DD=DD+TAV
        ELSE
          DD=DD+TAV/6.
        ENDIF
```

```
      IF(DD.LT.14) ITHAW=I
      STDAY(I,1)=0.0
      STDAY(I,2)=0.0
      STDAY(I,3)=0.0
     ENDDO
C
C  DAILY TIME LOOP
     DO I=ITHAW,365
      SOLRAD=WTHR(I,2)
      TEMPMX=WTHR(I,3)
      TEMPMN=WTHR(I,4)
      PRECIP=WTHR(I,5)
C      RESIDUE COVER
      IF(I.LT.180.AND.ICRNPL.LE.4)  THEN
        RC=0.30
      ELSE
        RC=0.65
      ENDIF
      SWR=AMIN1(1.,(SW(1)-LL)/(DUL-LL))
      IF(SWR.LT.0.9) THEN
        SUMES1=SOIL(S,4)
        SUMES2=25.-27.8*SWR
        T=(SUMES2/3.5)**2
      ELSE
        SUMES1=100.-SWR*100.
        SUMES2=0.
        T=0.
      ENDIF
      WINF=PRECIP
      FLUX=0.1*PRECIP
C
C  CALCULATE INFILTRATION, DRAINAGE AND SATURATED FLOW
      DO L=1,NLAYR
        HOLD=(SAT-SW(L))*DLAYR(L)
        IF ((FLUX.EQ.0.0) .OR. (FLUX.LE.HOLD)) THEN
          SW(L)=SW(L)+FLUX/DLAYR(L)
          IF(SW(L).GT.DUL+0.003)  THEN
            DRAIN=(SW(L)-DUL)*SOIL(S,12)*DLAYR(L)
            SW(L)=SW(L)-DRAIN/DLAYR(L)
            FLUX=DRAIN
          ELSE
            FLUX=0.
          ENDIF
        ELSE
          DRAIN=(SAT-DUL)*SOIL(S,12)*DLAYR(L)
```

```
          SW(L)=SAT-DRAIN/DLAYR(L)
          FLUX=FLUX-HOLD+DRAIN
        ENDIF
      ENDDO
C
C  CALCULATE SOIL EVAPORATION
C       POTENTIAL EVAPORATION
      TD=0.6*TEMPMX+0.4*TEMPMN
      EEQ=SOLRAD*(1.-0.5*RC)*(0.00488-0.00437*SOIL(S,3))*(TD+29.)
      EOS=EEQ*1.1
      IF(TEMPMX.GT.35) EOS=EEQ*((TEMPMX-35.)*0.05+1.1)
      IF(TEMPMX.LT.5) EOS=EEQ*0.01*EXP(0.18*(TEMPMX+20.))
C
C       ACTUAL SOIL EVAPORATION
      IF(SUMES1.GE.SOIL(S,4).AND.WINF.GE.SUMES2)  THEN
        WINF=WINF-SUMES2
        SUMES1=SOIL(S,4)-WINF
        T=0
        IF(WINF.GT.SOIL(S,4)) SUMES1=0.0
        SUMES1=SUMES1+EOS
        IF(SUMES1.GT.SOIL(S,4)) THEN
          ES=EOS-0.4*(SUMES1-SOIL(S,4))
          SUMES2=0.6*(SUMES1-SOIL(S,4))
          T=(SUMES2/3.5)**2
        ELSE
          ES=EOS
        ENDIF
      ELSEIF(SUMES1.GE.SOIL(S,4).AND.WINF.LT.SUMES2)  THEN
        T=T+1.
        ES=3.5*T**0.5-SUMES2
        IF(WINF.GT.0) THEN
          ESX=0.8*WINF
          IF(ESX.LE.ES) ESX=ES+WINF
          ES=AMIN1(EOS,ESX)
        ELSEIF(ES.GT.EOS) THEN
          ES=EOS
        ENDIF
        SUMES2=SUMES2+ES-WINF
        T=(SUMES2/3.5)**2
      ELSEIF(WINF.GE.SUMES1) THEN
        SUMES1=EOS
        IF(SUMES1.GT.SOIL(S,4)) THEN
          ES=EOS-0.4*(SUMES1-SOIL(S,4))
          SUMES2=0.6*(SUMES1-SOIL(S,4))
          T=(SUMES2/3.5)**2
```

```
        ELSE
          ES=EOS
        ENDIF
      ELSE
        SUMES1=SUMES1-WINF+EOS
        IF(SUMES1.GT.SOIL(S,4)) THEN
          ES=EOS-0.4*(SUMES1-SOIL(S,4))
          SUMES2=0.6*(SUMES1-SOIL(S,4))
          T=(SUMES2/3.5)**2
        ELSE
          ES=EOS
        ENDIF
      ENDIF
      SW(1)=AMAX1(LL*SWEF,SW(1)-ES*0.1/DLAYR(1))
C
C  ESTIMATE PLANT EXTRACTED MOISTURE (0.3 CM/DAY FROM LOWER
LAYER)
      IF(I.GT.150.AND.I.LT.270) THEN
        SW(4)=AMAX1(LL,SW(4)-0.3/DLAYR(4))
      ENDIF
C
C  CALCULATE UNSATURATED FLOW BELOW FIELD CAPACITY
      DO J=1,NLAYR-1
        M=J+1
        THET1=AMAX1(0.,SW(J)-LL)
        THET2=AMAX1(0.,SW(M)-LL)
        DBAR=AMIN1(100.,0.88*EXP(35.4*(THET1+THET2)*0.5))
        FLOW=DBAR*(THET2-THET1)/((DLAYR(J)+DLAYR(M))*0.5)
        IF(FLOW.LT.0) THEN
          FLOW=AMAX1(FLOW,(SW(M)-SW(J))*DLAYR(J))
        ELSE
          FLOW=AMIN1(FLOW,(DUL-SW(J))*DLAYR(J))
        ENDIF
        SW(J)=SW(J)+FLOW/DLAYR(J)
        SW(M)=SW(M)-FLOW/DLAYR(M)
      ENDDO
C
C  DETERMINE IF DAY IS SUITABLE FOR FIELD WORK
      IF(I.LT.180) THEN
        IF(SW(1).LE.SOIL(S,13)*DUL.AND.SW(2).LE.
     +     SOIL(S,13)*DUL.AND.SW(3).LE.SOIL(S,14)*DUL)  THEN
C          DAY IS SUITABLE FOR TILLAGE AND PLANTING
          STDAY(I,1)=1
        ELSE
          STDAY(I,1)=0
```

```
          ENDIF
        ELSE
          IF(SW(1).LE.SOIL(S,15)*DUL.AND.SW(2).LE.
     +      SOIL(S,15)*DUL.AND.SW(3).LE.SOIL(S,16)*DUL)  THEN
C           DAY IS SUITABLE FOR TILLAGE AND PLANTING
            STDAY(I,1)=1
          ELSE
            STDAY(I,1)=0
          ENDIF
        ENDIF
        IF(I.LT.180) THEN
          IF(SW(1).LT.SOIL(S,15)*DUL.AND.SW(2).LE.SOIL(S,15)*DUL.AND.
     +      SW(3).LE.SOIL(S,16)*DUL)  THEN
C           DAY IS SUITABLE FOR SURFACE SPREADING (SPRING)
            STDAY(I,2)=1
          ELSE
            STDAY(I,2)=0
          ENDIF
        ELSE
          IF(SW(1).LT.SOIL(S,17)*DUL.AND.SW(2).LE.SOIL(S,17)*DUL.AND.
     +      SW(3).LE.SOIL(S,18)*DUL)  THEN
C            DAY SUITABLE FOR SURFACE SPREADING OR CORN HARVEST
(FALL)
            STDAY(I,2)=1
          ELSE
            STDAY(I,2)=0
          ENDIF
        ENDIF
        STDAY(I,3)=STDAY(I,2)
        IF(ISPD.GE.13.AND.ISPD.LE.16)  THEN
C          MANURE INJECTION, SAME SUITABLE DAYS AS TILLAGE
          STDAY(I,2)=STDAY(I,1)
        ENDIF
      ENDDO
C
C  SUMMARIZE DATA FOR DETAILED OUTPUT
      DO I=1,12
        SDP1(NTHYR,I)=0.0
        SDP2(NTHYR,I)=0.0
      ENDDO

      L=0
      DO M=1,12
        DO I=1,ND(M)
          L=L+1
```

```
      SDP1(NTHYR,M)=SDP1(NTHYR,M)+STDAY(L,1)
      SDP2(NTHYR,M)=SDP2(NTHYR,M)+STDAY(L,3)
     ENDDO
    ENDDO
C
```

APPENDIX B

Annual Feed and Manure Production, System Costs and Net Return

Table B.1 Annual feed and manure production, system costs and net return with conventional tillage and four manure handling systems on a high producing, 60-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
CONVENTIONAL TILLAGE					
Feed production and utilization					
Preharvest alfalfa production	t DM	348	348	348	348
High quality alf. hay production	t DM	64	67	67	67
Low quality alf. hay production	t DM	21	17	17	17
Alfalfa silage production	t DM	198	199	199	199
Corn silage production	t DM	128	129	129	129
High-moisture corn production	t DM	---	---	---	---
Corn grain production	t DM	124	125	125	125
Corn grain purchased (sold)	t DM	(27)	(29)	(29)	(29)
Alfalfa purchased (sold)	t DM	31	30	30	30
Soybean meal purchased	t DM	25	25	25	25
Average milk production	L/cow	9,297	9,308	9,312	9,315
Manure production and utilization					
Manure, bedding and waste handled	t WM	3,671	3,669	4,890	2,256
Manure applied to alfalfa land	t WM	1,487	1,491	1,990	919
Manure applied to corn grain	t WM	1,474	1,469	1,956	902
Manure applied to corn silage	t WM	711	710	944	435
Manure nitrogen to cropland	t	8	7	7	6
Manure phosphorus to cropland	t	3	3	3	3
Manure potassium to cropland	t	10	10	10	10
Manure fertilizer value credit	$	4,515	4,461	4,463	4,321
System costs and returns					
System machinery cost	$	34,363	33,138	33,660	32,847
System fuel and electric cost	$	3,934	3,690	3,576	3,414
System feed and manure storage cost	$	9,412	9,421	9,828	6,516
System labor cost	$	12,168	12,210	11,684	11,726
Seed, fertilizer and chemical cost	$	7,281	7,335	7,333	7,475
Corn grain drying cost	$	2,494	2,469	2,447	2,444
Land charge	$	8,000	8,000	8,000	8,000
Feed and bedding purchased	$	9,543	9,330	9,310	9,326
Income from milk sales	$/cow	2,557	2,560	2,561	2,562
Total feed and manure cost	$/cow	1,453	1,427	1,431	1,362
Other major costs	$/cow	1,446	1,446	1,446	1,446
Net return	$/cow	-342	-313	-316	-246

Table B.2 Annual feed and manure production, system costs and net return with mulch tillage and four manure handling systems on a high producing, 60-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
MULCH-TILLAGE					
Feed production and utilization					
Preharvest alfalfa production	t DM	348	348	348	348
High quality alf. hay production	t DM	64	67	67	67
Low quality alf. hay production	t DM	21	18	18	18
Alfalfa silage production	t DM	196	197	197	197
Corn silage production	t DM	144	144	144	144
High-moisture corn production	t DM	---	---	---	---
Corn grain production	t DM	119	119	118	118
Corn grain purchased (sold)	t DM	(24)	(24)	(24)	(24)
Alfalfa purchased (sold)	t DM	17	16	16	16
Soybean meal purchased	t DM	27	27	27	27
Average milk production	L/cow	9,359	9,365	9,369	9,369
Manure production and utilization					
Manure, bedding and waste handled	t WM	3,658	3,657	4,876	2,250
Manure applied to alfalfa land	t WM	1,482	1,474	1,973	912
Manure applied to corn grain	t WM	1,382	1,388	1,843	850
Manure applied to corn silage	t WM	794	796	1,060	489
Manure nitrogen to cropland	t	8	7	7	6
Manure phosphorus to cropland	t	3	3	3	3
Manure potassium to cropland	t	9	9	9	9
Manure fertilizer value credit	$	4,500	4,435	4,439	4,298
System costs and returns					
System machinery cost	$	33,714	32,535	33,006	32,206
System fuel and electric cost	$	3,829	3,598	3,479	3,311
System feed and manure storage cost	$	9,495	9,496	9,902	6,591
System labor cost	$	12,001	12,011	11,471	11,492
Seed, fertilizer and chemical cost	$	7,378	7,443	7,439	7,580
Corn grain drying cost	$	2,357	2,347	2,332	2,330
Land charge	$	8,000	8,000	8,000	8,000
Feed and bedding purchased	$	9,080	8,980	9,044	9,055
Income from milk sales	$/cow	2,574	2,575	2,576	2,576
Total feed and manure cost	$/cow	1,431	1,407	1,411	1,343
Other major costs	$/cow	1,446	1,446	1,446	1,446
Net return	$/cow	-303	-278	-281	-213

Table B.3 Annual feed and manure production, system costs and net return with modified no-till and four manure handling systems on a high producing, 60-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
MODIFIED NO-TILL					
Feed production and utilization					
Preharvest alfalfa production	t DM	---	348	348	348
High quality alf. hay production	t DM	---	67	67	67
Low quality alf. hay production	t DM	---	17	17	17
Alfalfa silage production	t DM	---	199	199	199
Corn silage production	t DM	---	129	129	129
High-moisture corn production	t DM	---	---	---	---
Corn grain production	t DM	---	126	125	125
Corn grain purchased (sold)	t DM	---	(29)	(29)	(29)
Alfalfa purchased (sold)	t DM	---	30	30	30
Soybean meal purchased	t DM	---	25	25	25
Average milk production	L/cow	---	9,312	9,315	9,315
Manure production and utilization					
Manure, bedding and waste handled	t WM	---	3,667	4,889	2,256
Manure applied to alfalfa land	t WM	---	1,488	1,986	917
Manure applied to corn grain	t WM	---	1,471	1,958	904
Manure applied to corn silage	t WM	---	709	944	436
Manure nitrogen to cropland	t	---	6	6	6
Manure phosphorus to cropland	t	---	3	3	3
Manure potassium to cropland	t	---	10	10	10
Manure fertilizer value credit	$	---	4,314	4,315	4,318
System costs and returns					
System machinery cost	$	---	32,110	32,573	31,294
System fuel and electric cost	$	---	3,468	3,349	3,165
System feed and manure storage cost	$	---	9,420	9,827	6,516
System labor cost	$	---	11,678	11,135	11,091
Seed, fertilizer and chemical cost	$	---	8,330	8,329	8,326
Corn grain drying cost	$	---	2,477	2,468	2,466
Land charge	$	---	8,000	8,000	8,000
Feed and bedding purchased	$	---	9,268	9,312	9,325
Income from milk sales	$/cow	---	2,561	2,562	2,562
Total feed and manure cost	$/cow	---	1,413	1,417	1,336
Other major costs	$/cow	---	1,446	1,446	1,446
Net return	$/cow	---	-298	-301	-220

Table B.4 Annual feed and manure production, system costs and net return with conventional tillage and four manure handling systems on a high producing, 150-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
CONVENTIONAL TILLAGE					
Feed production and utilization					
Preharvest alfalfa production	t DM	751	753	753	753
High quality alf. hay production	t DM	130	129	129	129
Low quality alf. hay production	t DM	48	56	56	56
Alfalfa silage production	t DM	447	443	443	443
Corn silage production	t DM	446	446	446	446
High-moisture corn production	t DM	198	220	220	220
Corn grain production	t DM	2	8	8	9
Corn grain purchased (sold)	t DM	19	9	(7)	(14)
Alfalfa purchased (sold)	t DM	17	17	17	17
Soybean meal purchased	t DM	103	102	103	103
Average milk production	L/cow	9,507	9,509	9,498	9,498
Manure production and utilization					
Manure, bedding and waste handled	t WM	9,061	9,052	12,061	5,565
Manure applied to alfalfa land	t WM	3,985	3,910	5,191	2,391
Manure applied to corn grain	t WM	2,492	2,543	3,454	1,610
Manure applied to corn silage	t WM	2,583	2,598	3,416	1,564
Manure nitrogen to cropland	t	20	18	18	16
Manure phosphorus to cropland	t	7	7	7	7
Manure potassium to cropland	t	23	23	23	23
Manure fertilizer value credit	$	10,764	10,535	10,567	10,308
System costs and returns					
System machinery cost	$	52,185	51,019	51,184	50,028
System fuel and electric cost	$	8,190	7,903	7,634	7,214
System feed and manure storage cost	$	13,722	13,729	14,756	9,279
System labor cost	$	21,413	21,052	20,015	20,025
Seed, fertilizer and chemical cost	$	16,896	17,125	17,093	17,352
Corn grain drying cost	$	34	57	139	163
Land charge	$	18,125	18,125	18,125	18,125
Feed and bedding purchased	$	38,810	37,478	35,952	35,214
Income from milk sales	$/cow	2,614	2,615	2,612	2,612
Total feed and manure cost	$/cow	1,129	1,110	1,099	1,049
Other major costs	$/cow	1,260	1,260	1,260	1,260
Net return	$/cow	225	245	253	303

Table B.9 Annual feed and manure production, system costs and net return with modified no-till and four manure handling systems on a high producing, 250-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
MODIFIED NO-TILL					
Feed production and utilization					
Preharvest alfalfa production	t DM	---	1,390	1,390	1,390
High quality alf. hay production	t DM	---	210	210	210
Low quality alf. hay production	t DM	---	139	139	139
Alfalfa silage production	t DM	---	817	817	817
Corn silage production	t DM	---	593	593	593
High-moisture corn production	t DM	---	304	304	304
Corn grain production	t DM	---	121	121	120
Corn grain purchased (sold)	t DM	---	(65)	(65)	(64)
Alfalfa purchased (sold)	t DM	---	56	56	56
Soybean meal purchased	t DM	---	165	165	165
Average milk production	L/cow	---	9,520	9,520	9,520
Manure production and utilization					
Manure, bedding and waste handled	t WM	---	15,025	20,033	9,246
Manure applied to alfalfa land	t WM	---	7,005	9,324	4,311
Manure applied to corn grain	t WM	---	4,843	6,473	2,980
Manure applied to corn silage	t WM	---	3,177	4,237	1,955
Manure nitrogen to cropland	t	---	28	28	28
Manure phosphorus to cropland	t	---	12	12	12
Manure potassium to cropland	t	---	39	39	39
Manure fertilizer value credit	$	---	17,617	17,611	17,634
System costs and returns					
System machinery cost	$	---	71,908	70,417	68,778
System fuel and electric cost	$	---	12,241	11,737	10,966
System feed and manure storage cost	$	---	20,437	22,119	14,229
System labor cost	$	---	27,403	26,134	25,786
Seed, fertilizer and chemical cost	$	---	31,643	31,649	31,626
Corn grain drying cost	$	---	2,301	2,315	2,263
Land charge	$	---	31,250	31,250	31,250
Feed and bedding purchased	$	---	54,504	54,592	54,573
Income from milk sales	$/cow	---	2,618	2,618	2,618
Total feed and manure cost	$/cow	---	1,007	1,001	958
Other major costs	$/cow	---	1,254	1,254	1,254
Net return	$/cow	---	357	363	406

Table B.10 Annual feed and manure production, system costs and net return with conventional tillage and four manure handling systems on a high producing, 400-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
CONVENTIONAL TILLAGE					
Feed production and utilization					
Preharvest alfalfa production	t DM	2,219	2,219	2,219	2,219
High quality alf. hay production	t DM	344	344	343	344
Low quality alf. hay production	t DM	201	201	201	201
Alfalfa silage production	t DM	1,298	1,298	1,299	1,298
Corn silage production	t DM	1,068	1,068	1,068	1,068
High-moisture corn production	t DM	380	380	380	380
Corn grain production	t DM	232	231	238	237
Corn grain purchased (sold)	t DM	(59)	(59)	(65)	(65)
Alfalfa purchased (sold)	t DM	13	13	13	13
Soybean meal purchased	t DM	268	268	268	269
Average milk production	L/cow	9,588	9,588	9,586	9,586
Manure production and utilization					
Manure, bedding and waste handled	t WM	23,916	23,916	31,887	14,717
Manure applied to alfalfa land	t WM	11,310	11,272	15,030	6,937
Manure applied to corn grain	t WM	6,917	6,915	9,270	4,281
Manure applied to corn silage	t WM	5,689	5,729	7,587	3,499
Manure nitrogen to cropland	t	53	49	49	43
Manure phosphorus to cropland	t	19	19	19	19
Manure potassium to cropland	t	62	62	62	62
Manure fertilizer value credit	$	29,211	28,711	28,715	28,041
System costs and returns					
System machinery cost	$	125,230	120,845	116,155	116,888
System fuel and electric cost	$	24,387	23,672	22,150	21,596
System feed and manure storage cost	$	28,657	28,656	31,360	19,882
System labor cost	$	48,925	48,423	45,870	46,660
Seed, fertilizer and chemical cost	$	44,635	45,145	45,131	45,805
Corn grain drying cost	$	4,569	4,542	4,525	4,499
Land charge	$	50,000	50,000	50,000	50,000
Feed and bedding purchased	$	86,317	86,365	85,633	85,699
Income from milk sales	$/cow	2,637	2,637	2,636	2,636
Total feed and manure cost	$/cow	1,032	1,019	1,002	978
Other major costs	$/cow	1,197	1,197	1,197	1,197
Net return	$/cow	408	421	437	462

Table B.13 Annual feed and manure production, system costs and net return with mulch tillage and four manure handling systems on a high producing, 800-cow dairy farm.

Production or cost parameter	Unit	Slurry injection tankers	Slurry spreader tankers	Liquid irrigation	Semi-solid V-tanker
MULCH-TILLAGE					
Feed production and utilization					
Preharvest alfalfa production	t DM	4,210	4,210	4,209	4,209
High quality alf. hay production	t DM	619	619	622	622
Low quality alf. hay production	t DM	444	444	442	442
Alfalfa silage production	t DM	2,563	2,563	2,561	2,561
Corn silage production	t DM	2,161	2,161	2,161	2,161
High-moisture corn production	t DM	652	652	652	652
Corn grain production	t DM	521	533	580	582
Corn grain purchased (sold)	t DM	(60)	(72)	(121)	(123)
Alfalfa purchased (sold)	t DM	67	67	71	71
Soybean meal purchased	t DM	528	528	528	528
Average milk production	L/cow	9,636	9,636	9,634	9,634
Manure production and utilization					
Manure, bedding and waste handled	t WM	47,735	47,735	63,645	29,374
Manure applied to alfalfa land	t WM	22,464	22,409	29,884	13,794
Manure applied to corn grain	t WM	13,687	13,715	18,391	8,517
Manure applied to corn silage	t WM	11,585	11,612	15,369	7,063
Manure nitrogen to cropland	t	105	96	96	85
Manure phosphorus to cropland	t	37	37	37	37
Manure potassium to cropland	t	124	124	124	124
Manure fertilizer value credit	$	57,362	56,328	56,421	55,134
System costs and returns					
System machinery cost	$	220,187	213,721	202,635	204,362
System fuel and electric cost	$	54,889	51,729	50,310	48,609
System feed and manure storage cost	$	53,415	53,462	59,104	39,755
System labor cost	$	95,746	93,088	87,694	90,551
Seed, fertilizer and chemical cost	$	87,297	88,331	88,238	89,525
Corn grain drying cost	$	10,873	10,911	11,328	11,137
Land charge	$	97,500	97,500	97,500	97,500
Feed and bedding purchased	$	181,422	180,103	174,541	174,431
Income from milk sales	$/cow	2,650	2,650	2,649	2,649
Total feed and manure cost	$/cow	1,002	986	964	945
Other major costs	$/cow	1,146	1,146	1,146	1,146
Net return	$/cow	502	518	539	558