CHAPTER II
LITERATURE REVIEW

2.1 Sugarcane : botanical description

Sugarcane (*Saccharum*) is a genus of 6 to 37 species (depending on taxonomic interpretation) of tall perennial grasses (family Poaceae, tribe Andropogoneae), native to warm temperate to tropical regions of the Old World. Sugarcane was originally from tropical South Asia and Southeast Asia (Wikipedia, 2009). Hunsigi (1993) reported that the genus *Saccharum* could be divided into 6 species namely, *S. barberi, S. sinense, S. robustum, S. edule, S. spontaneum* and *S. officinarum*. Different species likely originated in different locations, with *S. barberi* and *S. sinense* originating in India and China, respectively. The very vigorous but low sugar and high fibre species, *S. robustum,* is found only in Papua-New Guinea. *S. edule,* is also not very sweet but produces an edible flower, like an elongated cauliflower, which is a delicacy throughout Melanesia and Polynesia. The very vigorous but low-sugar species, *S. spontaneum,* is found around streams and rivers throughout Papua-New Guinea and Southeast Asia. The archetypal soft, sweet chewing "noble canes" belonging to the species *S. officinarum* are well-tended "garden canes", low in fibre, self-detrashing, high in sucrose and used for chewing and sugar making (Hunsigi, 1993). All of the sugar cane species interbreed, and the major commercial cultivars are complex hybrids (Wikipedia, 2009).

Sugarcane is a tropical plant and cultivated varieties are all grown in warm countries. The optimum conditions are tropical and dry during growth (20 to 38 °C) and cool during ripening periods (10 to 20 °C) (Humbert, 1968; Blackburn, 1984). It is grown from sea level to 1500 m above sea level and between the latitudes 36.7 °N and 31.0 °S. But as the elevation increases, so the temperature decreases and the crop requires longer period for growth and development (Hunsigi, 1993). The soil should be at least 50-80 cm deep and ground water depth more than 160 cm (Sooksathan, 1980; Sooksathan and Poolkate, 1984). Soil should be loose, well aerated and well drained. Bulk density should be less than 1.2 g cm^{-3} with texture of either loam, silt loam or clay loam. Optimum chemical soil properties include pH of 5.6-7.3, organic

matter 1.5-2.5 percent, available phosphorus 10-20 ppm, exchangeable K and Ca 0.21-0.39 and 0.55-1.25 cmol kg^{-1}, respectively. Cation exchange capacity should be more than 15 cmol kg^{-1}, EC less than 2.5 dS m^{-1}, and base saturation more than 75% (Prammanee, 2001).

The growth of sugarcane can be divided into five phases (Bull, 2000) :

1) Germination where the plant is established and tillers initiated.

2) Early growth where the leaf canopy is established and maximum growth or elongation of the storage organ (the stalk) occurs.

3) Maturation where stalk elongation slows down and sugar storage or ripening dominates.

4) Flowering where vegetative growth ceases and an arrow (flower) is produced.

5) Ratooning where stalks are harvested and crop re-growth occurs from underground buds of the several stalks.

The growth phases constitute the life cycle of sugarcane in its normal production and they are affected by environmental factors.

Sugarcane propagation is through stem cuttings of immature canes 8-12 months old. These are called "setts", "seed", "seed- cane" or "seed-pieces". It takes 12,500 - 20,000 setts to plant in one hectare (Purseglove, 1974). The setts are lightly covered with soil until they sprout (10-14 days) and then the sides of the furrow are turned inward (McIntosh, 1988). Sugarcane is a perennial crop which usually produces crops for about 3-6 years before being replanted. The first crop is called the "plant crop" and takes 9-24 months to mature, depending on location (Purseglove, 1974).

2.2 Sugarcane production

2.2.1 World production

In 2007, sugarcane production area of the world was 21 million ha, produced 1,557 million Mg of millable cane with average yield of 70.9 Mg ha^{-1}. The largest cane producers are Brazil, India, China, Mexico, Pakistan and Thailand, accounting for 74% of total world area (Food and Agriculture Organization of the United

Nations, 2009). Sugar production from sugarcane of the world was 163.3 million Mg, Thailand produced 6.9 million Mg (4.2% of the world) (United States Department of Agriculture USDA, 2009). Uses of sugar cane include the production of sugar, molasses, rum, soda, and ethanol for fuel. The bagasse that remains after sugarcane crushing may be burned to provide both heat and electricity used in the mill and sold to the local or electrical authority. It may also be used as raw material for paper, and cardboard.

2.2.2 Sugarcane production in Thailand

In 2007, Thailand was the world's fifth largest sugar producer and the second largest exporter. Total fresh cane production was 64.4 million Mg from the area of 1.01 million ha to produce 6.9 million Mg of sugar. Sugar production of Thailand represented only about 4.2% of the world sugar production (United States Department of Agriculture USDA, 2009). However, domestic consumption was 1.65-1.85 million Mg, leaving large amounts of sugar to be exported, 3.3-4.5 million Mg per year. In 2008, income from exporting sugarcane products was 40,940 million baht and rank 3rd of income from crops after rice and rubber (Office of Agricultural Economics, 2007b). According to the Office of Agricultural Economics (2007b) there were 223,213 households under sugarcane production and 47 sugar mills scatter in the central, western, eastern and northeastern in 2006. The yield of cane was relatively low of 49 Mg ha^{-1}.

2.2.3 Sugarcane production in Northeast Thailand

The agricultural area of Thailand is 20.84 million ha of which 9.24 million ha is in the Northeast region. Major crops cultivation in the Northeast was rice, followed by cassava, sugarcane and maize which occupied 5.234, 0.660, 0.303 and 0.208 million ha, respectively. Field crop cultivation in the Northeast occupied 3.48 % of total land area and was the second largest area follow paddy that accounted 11.69% of total land area of the country. The production value of rice, cassava, sugarcane and maize at farm prices were 69,193, 18,429, 10,779 and 3,750 million baht, respectively (Table 2.1). Sugar cane yield was 47.056 Mg ha^{-1} and farm price of fresh cane was 688 baht Mg^{-1} (Office of Agricultural Economics, 2007a and 2007b).

Table 2.1 Major field crops production in the Northeast of Thailand in 2006/07.

Crops	Planting area (1,000 ha)	Production (1,000 Mg)	Yield (kg ha^{-1})	Farm price (baht Mg^{-1})	Farm value (million baht)
Rice	5,234	10,292	2,056	6,723	69,193
Cassava	660	14,286	22,544	1,290	18,429
Sugarcane	333	15,667	47,056	688	10,779
Maize	208	688	3,525	5,450	3,750

(Office of Agricultural Economics, 2007a and 2007b).

According to Chetthamrongchai et al. (2001), total production cost of sugarcane in the Northeast in 1999/2000 was about 20,581 baht per ha which 80% was variable cost, labor and material, while fixed cost, such as depreciation and land rent, accounted for less than 20 per cent. Labor costs contributed the highest share of the total farm-level costs (43.5%), followed by costs of planting material, chemicals and fertilizer accounting for 41.2%. This cost structure indicates the comparative advantage of the Northeast region from the cheaper labor cost standpoint. The rate of return at farm level is about 37%.

2.2.3.1 Cropping system of sugarcane in the Northeast

More than 90% of sugarcane planting areas are under rain-fed. There are two planting periods.

1). Early rainy season planting. This system is conducted in clay soil of the Central, the West and Northeast regions where cane is mainly planted from April to June under rainfed condition. The cane normally is harvested at the age less than one year therefore sugar content is low relative to the late rainy season planting. Since the time of planting is from April to June, most sugarcane under this system is grown as a continuous monocrop. In areas where water is available for initial emergence, sugarcane is planted during February to April.

2). *Late rainy season planting.* This system is commonly practiced and covers 80 % of total area in sandy soil especially in the northeastern and eastern of the region. Sugarcane is planted at the end of the rainy season, during October to

November or later until soil moisture is not adequate for emergence. The cane may be harvested at the age more than one year, therefore sugar content is higher than those planted in the early rainy season. For successful crops this zone should receive more than 1,200 mm per year of rainfall with appropriate distribution especially during February to April which are the critical crop growth phase. This system of planting will provide 5-6 months fallow period between the last ratoon harvest and planting a new sugarcane crop.

2.2.3.2 Sugarcane cultural practices in Northeast Thailand

Several sugarcane varieties were released and recommended to farmers by the Office of the Cane and Sugar Board under the Ministry of Industry, the Department of Agriculture and one private company. There were reports that during the crop-year 1998-1999 the most common variety in the northeastern region was Phill 66-07 occupying more than 40 per cent of the total planted area. The second most popular variety was U-Thong I, which accounted for 13 percent, while other varieties combined were planted on the remaining 47 per cent (Chetthamrongchai et al., 2001). Recently, K8892, U-Thong 1 and Khon Kaen 3 are widely grown in sandy soil area while K84200 and new released cultivars are adopted in clay soil.

Soil preparation

Deep ploughing to at least 30 cm is recommended for normal condition, however a subsoiler is needed when hard pans are found. In rain-fed conditions, a second ploughing should be practiced to further break soil down into a fine tilth, so that it can maintain its moisture for a longer time. This is important when sugarcane is planted at the end of the rainy season.

Planting method

Sugarcane is normally planted either as two-or three- budded setts in furrows, or as whole stalks cut into 15 cm lengths and covered with soil. Most cane is planted manually, but machine planting is also practiced. Row and plant spacings are 1.0-1.3 x 0.5 m for manual planting. The row spacing is 1.4-1.6 m for machine planting.

Nutrient requirement and fertilization

Sugarcane produces large amount of biomass compared to other field crops, e.g. cassava and maize. The amount of nutrients removed from soil had been reported to be N 0.56-1.2 kg, P_2O_5 0.38-0.82 kg, K 1.0-2.5 kg, Ca 0.25-0.60 kg, Mg 0.20-0.35 kg, Na 0.02-0.2 kg and S or SO_4 2.0-2.7 kg ha^{-1} (Zende, 1990). In Thailand, the total biomass, including leaf, root and stem of 1 Mg sugarcane composed of 0.84 kg N, 0.79 kg P and 1.98 kg K (Prammanee, 2001). High removal of nutrients from soil as well as burnt field prior to harvest caused a rapidly decline in soil productivity. High rates of mineral fertilizers have been recommended for sugarcane production. The general recommendation rates for fertilizer application in <1 % O.M. soil are 112.5 kg N, 37.5 kg P and 37.5 kg K ha^{-1} (Taksina Sansayawichai, personal communication Dec. 10, 2008).

The main input used for sugarcane production is chemical fertilizer (N-P_2O_5-K_2O) in various grades such as 15-15-15, 46-0-0, 21-0-0, and 16-20-0. On average, the farmers apply chemical fertilizers at the rate of 440-460 kg ha^{-1} with 2-3 split applications. The rates of fertilizer application were not different among farms with a land area smaller than 3 ha. In the large-scale farms with a size above 3.36 ha, increases an application rate of about 630 kg ha^{-1} has been reported (Thailand Development Research Institute, 2000) .

In the Northeast of Thailand many farmers cannot afford sufficient amounts of mineral fertilizers to their crops. The reluctant in application of mineral fertilizer is caused by erratic rainfall. Moreover, the use of N-fertilizer is low efficiency mainly due to loss of NH_4^+ and/or NO_3^- by leaching and by lateral flow. The application of inorganic fertilizers to maintain soil fertility is mainly limited by high cost.

Harvesting

More than 90% of cane harvesting is done manually. On average, one person can harvest a ton of cane in a day. The right time for harvesting sugarcane is when the crop is 12-14 months old. Burning prior or after harvesting cane is a common practice in the Northeast.

2.3 Soil fertility degradation and restoration under sugarcane in the Northeast

2.3.1 Soil fertility degradation

Light textured sandy soils are common throughout northeast Thailand. Population increase and land use change have resulted in a significant decline of the nutrient status of these soils, largely due to declining soil organic carbon in surface horizons. The key driving force associated with the chemical degradation of these soils is continuous tillage, which causes a loss of organic carbon and a decline in cation exchange capacity (CEC). Soil organic matter is particularly difficult to restore in tropical and sub-tropical environments where regular disturbance of the soil texture occurs during the preparation of seedbeds and weed control. This result is confirmed by other studies (Tangtrakarnpong and Vityakon, 2002). They showed that carbon contents of most soil organic matter pools are much lower in the upland cultivated fields than in the lowland paddies and the forest. In the upland fields, the degradation of soil organic matter pools was more severe under cassava than sugarcane because the latter returned more organic residues to the soil. Vityakon (2007) reported that cultivation of sugarcane in the Northeast did not lead to as low soil organic matter pools as cassava because sugarcane produces more organic residues than cassava. This results from high trash return from planted and ratoon sugarcane crops. (i.e. 6.5 and 4.1 Mg ha^{-1} respectively). In addition, large amount of residues returned are roots and stumps that remained in the soil after harvesting. Unfortunately, leaf litter is generally burnt to ease harvest and is one reason why soil fertility under sugarcane production rapidly declines. Another reason that may also contribute to a rapid decline in soil fertility is the amount of nutrients removed in crop yield (millable cane). Substantial amounts of nutrients have been reported to be removed in one Mg of millable cane yield (Zende, 1990). This might also lead to a rapid decline in soil fertility since sugarcane yield is generally high.

2.3.2 Soil fertility restorating

Since sugarcane has become predominant in the uplands, it has been observed that its cultivation has led to the clearing of trees in sugarcane fields at an accelerating rate. As mentioned above, soil fertility degradation can occur under continuous

sugarcane production. However, there are several strategies to improve soil fertility for sugarcane production.

1. Green manuring: This is a practice of fundamental importance within management systems used to recover low fertility soils, aiming to increase productivity of sugarcane (Zambello and Orlando Filho, 1981). The green manure crops commonly used are legumes since they normally have higher nutrient contents, when compared to other plants. Furthermore, they produce a large volume of green biomass in relatively short periods of time, and can fix atmospheric N in the order of 225 kg N ha^{-1} under optimal conditions (Cowing, 1982). Cane yields were increased by using green manure in combination with chemical fertilizers by increasing tillering, and nitrogen content (71.9 kg N ha^{-1}). Cane yields were increased from 16 to 20 Mg ha^{-1} in plant cane and 13 to 23 Mg ha^{-1} in ratoon cane (Prammanee et al., 1996). However, green manure legumes do not generate an economic return and are not accepted by small scale farmers who have limited resources (Whitmore et al., 2000). Grain legumes had been reported to increase soil organic matter and nutrient contents in several cropping systems (Hairiah et al., 2000; Basanta et al., 2003).

2) Crop rotation: This involves intercropping and alley crop species to break the sugarcane monoculture. Rotation of susceptible agronomic crops with crops that are not hosts for nematodes or are resistant to certain nematodes has been a successful nematode management strategy in many instances (Reddy et al., 1986). The continuous use of a monoculture may encourage certain diseases, weeds, or insects. The continuity of the pest cycle may be interrupted by an alternative crop. Well-fertilized thick stands of a graminaceous crop, such as corn, will produce more above-ground residues than legume and tillage will favor a more rapid decomposition of organic matter produced (Tisdale et al., 1999). Yadav (1995) found that sugarcane yields were significantly higher in the rice-sugarcane-ratoon rotation than in the *Sesbania*-sugarcane-ratoon rotation. This resulted in greater uptake of N in the former than in the latter rotation system. Vityakon et al. (2004) showed that a crop rotation of sugarcane and cassava can help to maintain crop yield levels. Cassava grown after sugarcane produced higher yields than continuous cassava cultivation because the residual chemical fertilizers from sugarcane and its organic residues enhanced soil fertility.

3) Changes in residue management: This may help sustained land productivity, and may have noticeable consequences in the global carbon and other nutrients budget when large areas are involved. The effects of retaining crop residues in farming systems have been reported by several authors and are generally known to be advantageous over burning and physical removal from the standpoint of nutrient cycling. Retention of residues improves the N economy of the cropping system and enhances crop productivity (Shah et al., 2003). Thompson (1966) has thoroughly investigated the effect of sugarcane residue mulching on the yield and quality of cane. Also, Tang et al. (1998) found 3 and 4% increases in the cane and sugar yields following sugarcane trashing but the disadvantage of this practice is that it allows the build up of pests and diseases. However, residue retention brings about the conservation of soil moisture, which is reflected in increases in stalk density, cane and sugar yields (Hunsigi, 1993).

The applications of by products from sugar mills (filtercake and bagasse) have been reported to increase sugarcane growth and yield by many researchers. Rungrattanakasin et al.(1995) reported that high rate of filtercake application (37.5 Mg ha^{-1}) produced more cane yield of 86.3 Mg ha^{-1}. Jongrauysub et al. (2001) found the application of filter cake at 50 Mg ha^{-1} increased sugarcane yield, micropore distribution, available moisture content and decreased soil infiltration but did not have any effect on soil bulk density. Several studies have shown advantages of using filtercake on soil fertility improvement in sugarcane production due to its high phosphorus and calcium concentrations, thus enabled sugarcane to absorb more nutrients. Besides, fitercake could also improve soil physical properties. Another by-product from sugar mills is bagasse. Sruttaporn et al. (1985) increased millable cane yield with the application of bagasse at 6.25 Mg ha^{-1} along with chemical fertilizer grade 12-10-15 at the rate of 625 kg ha^{-1}. Bagasse is high in fiber content thus it can be used to improve physical properties and also improve soil moisture holding capacity.

2.4 Green manure as a soil amendment

Green manure are crops used primarily as a soil amendment and a nutrient source for succeeding crops. Green manure from legumes may add N to cropping system through biological fixation, and the slow release of N from decomposing residues may be manipulated to match crops demand; (Agustin et al., 1999; Cline and Silvernail, 2002). Unlike mineral fertilizer, legumes can add N without transportation costs. Green manure can be used as alternatives to mineral fertilizers particularly for subsistence farmers whose resource base is small.

Legumes can play a major role in improving farm productivity as short-term fallow species (Hudgens, 2000). They can increase plant nutrient supply in the soil, especially N and improve soil physical characteristics, thereby improving crop yields (Müller et al., 1988; Yost and Evans, 1988.; Peoples and Craswell, 1992). Legumes can also provide good ground cover, thereby minimizing soil erosion through a reduction of raindrop impact and runoff (Lal et al., 1991).

A large number of plant species have been used as green manure crops in rice systems in India. In a broad sense, green manures include non-grain legumes (e.g., *Crotalaria, Sesbania*, and *Tephrosia*), grain legumes (e.g., cowpea (*Vigna unguiculata* (L.) Walp.), mung bean (*Vigna radiata* (L.) Wilczek), soybean (*Glycine max* (L.) Merr.), and peanut (*Arachis hypogaea* L.)), woody legumes (e.g., *Leucaena, Gliricidia, Pongamia*, and *Delonix* and weeds (e.g., *Calotropis, Ipomoea, Eichhornia*, and *Parthenium*) (Palaniappan et al., 1990 and 1991).

Peanut returned more than 60% of its total nitrogen to soil when its residues are returned to the field. Peanut residues contain >160 kg N ha^{-1}, are less lignified (~5% lignin), and are rich in N, as the crop is harvested while still green. If returned to the soil, groundnut residues can easily lead to doubling of maize yields on sandy soils (McDonagh et al., 1993), but even with groundnut, there is a net contribution from N_2 fixation only if the legume stover is returned to the soil or if substantial leaf fall occurs.

Pigeonpea can also enhance P availability to associated species in cropping systems (Ae et al., 1990; Snapp et al., 1998). Growth of this legume can result in P

release exceeding its requirement therefore the remainder is available to subsequent crops. Meanwhile , Balckom and Reeves (2005) reported that sunnhemp rotation with corn produced 7.6 Mg ha^{-1} of biomass and 144 kg ha^{-1} of biomass N content at 14 weeks after planting. Corn grain yield following sunnhemp averaged 6.9 Mg ha^{-1} whereas yield following winter fallow averaged 5.7 Mg ha^{-1}. Grain N content in corn following sunnhemp averaged 16.3 kg N ha^{-1} greater than those grown on fallow plots. Before first frost, sunnhemp produced excellent biomass to serve as a winter cover crop in corn production. In addition, it produced N equivalent to 58 kg ha^{-1} of N fertilizer during the 3 years period. Sunnhemp has a potential to be utilized as an alternative to winter legumes for ground cover and as an N source for a subsequent corn crop.

Mansoer et al. (1997) reported N fertilizer equivalent of 45 kg N ha^{-1} remaining in sunnhemp residue at the time of corn planting after it was mowed in the fall and allowed to decompose over the winter. He also reported that the majority of the N in sunnhemp was present in the leaves, which decomposed rapidly during the first 4 weeks after mowing. The remaining residue consisted of stems with a high C:N ratio, potentially lowering the N fertilizer equivalent of sunnhemp.

2.4.1 Estimation of N_2 fixation in green manure crops

Several methods are used to estimate the amount of N_2 fixed by legumes. These include acetylene reduction assay, ureide method, the N difference method, ^{15}N dilution techniques and the natural ^{15}N abundance method (Peoples et al., 1995). However, none is perfect as all have some limitations. Acetylene reduction assay (ARA) and ureide methods can measure N_2 fixation only at a particular point in time over the duration of the assay which is far from being measurement of the amount of N_2 fixed over an entire growing season (Giller and Wilson, 1991). Nitrogen difference method has the advantage of giving a measure of the total amount of N_2 fixed over the length of the experiment and is indispensable for many laboratory-based studies. However, this method is employed under conditions considered to be free of mineral N but which are in fact contaminated with N (Giller and Wilson, 1991). One of the most widely-used methods for integrated measurement of N_2 fixation is based on the principle of ^{15}N isotope dilution (Giller and Wilson, 1991).

The major assumption is that the $^{15}N/^{14}N$ ratio of N absorbed from soil (or water) is the same for the N_2-fixing plant and the non-fixing control. It is satisfied when ^{15}N enrichment of soil N available to the non-fixing and fixing system is constant during the experiment (it implies that ^{15}N added is equilibrated with soil N and labeling is constant with soil depth) or the N_2-fixing plant and the non-fixing control have similar N uptake patterns. On the other hand, the ^{15}N natural abundance, the N_2 fixing plant grown on an N-free growth medium must also be determined, as isotopic fraction of atmospheric N_2 can occur during N_2-fixation and this can differ between species. The ^{15}N dilution method is expensive in terms of ^{15}N fertilizer and measurement costs. The natural abundance method has an advantage of not having to be concerned over the ^{15}N fertilizer cost. However, the ^{15}N measurement requires higher performance mass spectrometer and the cost of measurement is still expensive (Giller and Wilson, 1991).

2.4.2 Chemical composition of green manure and its effect on decomposition and N release

Under similar environments, the chemical and physical characteristics of the residue determine the rate at which N is mineralized. Initial N, lignin and active polyphenol concentrations are the main chemical factors which determine decomposability and N release from residues (Vallis and Jones, 1973; Fox et al., 1990; Palm and Sanchez, 1991; Handayanto et al., 1994; Constantinides and Fownes, 1994a and 1994b).

The definition of quality attributes such as high or poor quality has to be put into the context of the use of these residues. Tian et al. (1993) argued that plant residues rich in N with small lignin contents enhanced crop performance through direct nutritional contributions whereas residues with high C:N ratio and lignin content do so through mulching effects improving the soil microclimate, controlling weeds and reducing soil erosion.

The C: N ratio and the concentrations of N and lignin have been, and still are looked upon as important characteristics governing the rate of decomposition and N mineralization. The theoretical optimum C:N ratio of the substrate for microbial growth should not exceed 25 (Swift et al., 1979) but both fungi and bacteria can

decompose plant materials with much higher C:N ratios. In a medium-term perspective, such as a vegetation season, residues with a C:N ratio greater than 30 in general result in a lowering of mineral N because of net immobilization (Stevenson, 1986); while residues with a C:N ratio below 20 lead to an increase in the mineral N level through net N mineralization. Quemada and Cabrera (1995), showed that net N mineralization may occur at higher C/N ratios than 20. Net immobilization at C:N ratios much lower than 20 is also common. Looking at the initial few weeks of decomposition, plant materials with low C:N ratios can cause net N immobilization initially (Jensen, 1994; Marstorp, 1996; Trinsroutrot et al., 2000). The total C:N ratio is consequently not the only variable to use when predicting N mineralization. One explanation for this is that the total C content in itself is not closely related to decomposition while the presence of carbohydrates with differing decomposition rates is of greater importance.

The plant cell is mainly composed of different polysaccharides, polypeptides and lignin, with varying rates of decomposition after litter formation. Oades (1988.) demonstrated that plant material composition, amount of plant material input, and proportions between plant parts and plant tissues are decisive for the formation of humus in soils. The chemical composition of plant material determines the availability of plant C to the soil decomposers, and will therefore have a crucial influence on the dynamics of N mineralization during decomposition. The importance of specific plant components in relation to C and N mineralization changes depending on factors such as plant species, and age (Haynes, 1986; Parton et al., 1987).

2.5 Decomposition of organic residues

2.5.1 Process of decomposition

Decomposition consists of 3 major processes which lead to mass loss of organic materials (Jonathan and Flanagan, 1989). These processes are :

-comminution: the physical breakdown of litter due to animal and abiotic processes such as abrasion by wind;

-catabolism: a biochemical process occurring through the action of microbial and animal enzymes; and

- leaching: a physical process where soluble materials from litter are lost through water percolating through the litter.

These processes can occur simultaneously or at different times. If they take place at different times, the sequence of occurrence is controlled by litter quality and environmental conditions, especially those related to edaphic (soil) conditions. For example, the litter which consists mostly of softer tissues are believed to be decomposed by microbes alone, that is catabolism can take place as soon as the litter is added to the soil, while that which consists mostly of refractory tissues will go through comminuting process before catabolism take place (Adulprasertsuk, 1993). Decomposition under field conditions is affected by climate (Vanlauwe et al., 1995) and faunal activity (Tian et al., 1992).

2.5.2 Factors affecting decomposition

Green manure decomposition and subsequent N release depend largely on residue quality and quantity, soil moisture and temperature and specific soil factors such as texture, mineralogy and acidity, biological activity and the presence of other nutrients (Myers et al., 1994).

2.5.2.1 Biological activities

External enzymes, produced by a few organisms, are required to break down the cellulose polymer. Fungi constitute the major organisms able to decompose cellulose. In general, the decomposition of cellulose takes place during aerobic conditions and is a slow process (Martin and Haider, 1986).

The majority of the decomposers is heterotrophic bacteria and fungi which obtain carbon (C) and energy from organic materials (Swift et al., 1979; Benbi and Richer, 2002). Generally, the initial decomposition of a plant material is performed by so-called opportunistic bacteria as well as fungi that are specialized in exploiting readily metabolized non-polymeric resources such as simple sugars, amino acids, starch and also some pectic substances. These organisms die as their nutrient resource is finished and the decomposition is taken over by species of bacteria and fungi with a slower growth rate, which are specialized in decomposition of more refractory structural carbohydrates. These substances are enzymatically broken down to smaller

molecules which then can be absorbed and utilized. Two important attributes of the decomposers are to be able to penetrate the protective surface of a substrate and to invade it at a cellular and molecular level (Swift et al., 1979; Heal et al., 1997). Many fungi accomplish this by producing specific hyphae, which mechanically penetrate the cuticularised surface of plants. The penetration is followed by exploitation of available substrates found within and between the cells that can be enzymatically attacked. An alternative course of action used by both bacteria and fungi is that of enzymatic attack on cutin and cell wall polymers by extracellular enzymes (Heal and Dighton, 1986; Sjökvist, 1995; Hammel, 1997). The water-soluble parts inside the plant cell may leach out from the cell if they come in contact with soil water and are decomposed (Collins et al., 1990).

Soil faunas, such as earthworms, collembola, mites, and nematodes, also affect decomposition of plant residues and soil organic matter, e.g. by comminution and mixing (Verhoef and Brussard, 1990; Wolters, 2000). The proportion of degradation originating from soil faunas is however small. The degradation of, for example, clover, only increased by approximately 5% in the presence of earthworms (Uvarov, 1982).

2.5.2.2 Chemical composition of organic residues

Decomposition processes can be predicted from initial litter chemistry (Aber and Melillo, 1980).

Substrate quality, referring to the chemical composition and physical structure of the litter type is influenced by plant nutrient status and carbon allocation patterns (Chapin et al., 1980; Vitousek and Hobbie, 2000). Nitrogen and phosphorus litter content have been linked to decay rates as a function of the nutritional requirements of decomposer communities (Melillo et al., 1982; Bargali et al., 1993). The types of carbon available in the litter substrate, such as lignin and cellulose, which vary in quantity, degradability and physical structure also regulate decay rates (Day, 1982; Berendse et al., 1987).

Originally, the C:N ratio and N availability were seen as a good predictor of decomposition (Waksman and Tenney, 1928). Subsequently, Vallis and Jones (1973) reported that soluble polyphenols affect N mineralization dynamics of organic

residues. Melillo et al. (1982) showed that the N and lignin content of hardwood leaf litter residues significantly affected their decomposition; while Handayanto et al. (1994) reported that the content of soluble polyphenols that were actively binding proteins was better related to decomposition than the total soluble polyphenol content.

Lignin is a large molecule consisting of phenolic groups composed of aromatic rings with three carbon side chains. Lignin is found in the primary and secondary cell wall as well as interwoven in the middle lamella bonded to parts of the cellulose and hemicelluloses forming a so-called ligno-polysaccharide complex (Bacic et al., 1988; Hatfield et al., 1999). In grasses, lignification is initiated through cross-linking of lignin to arabinose (Hatfield et al., 1999). The degree of lignification is generally known to reduce the decomposition of structural carbohydrates as it physically protects the cell wall against microbial attack (Swift et al., 1979; Berg et al., 1982; Wilson et al., 1993; Heredia et al., 1995; Chesson, 1997). Lignification of cell walls is generally considered as the premier impediment to decomposition of forage crops in ruminants (Deetz et al., 1993).

Lignin is relatively resistant against microbial decomposition and only few organisms are known to produce the enzymes necessary for degradation. White-rot fungi are the most abundant degraders of wood and are able to decompose lignin completely (Hammel, 1997). Other fungi such as soft-rot and brown-rot fungi may cause structural changes by attacking the side chains or by cleavage of certain bonds to expose the more easily decomposable cellulose (Martin and Haider, 1986; Chesson, 1997; Hammel, 1997). These species however are not able to complete degradation. A consortium of decomposer organisms most likely degrades lignin in soil (Kogel-Knabner, 2002). The degradation of lignin is an oxidative process and therefore no degradation takes place under anaerobic conditions (Kirk and Farrel, 1987).

The lignified cell walls of legumes contrast with those of grasses because they appear to be partly less digested than grass cell walls in the rumen environment (Wilson, 1993). The lignin in legumes probably is concentrated to only one tissue type, the xylem, rather than spread between several different tissue types, as in the grasses (Wilson et al., 1993). The lignin concentration in the xylem cells, especially in stems can be very high, preventing decomposition. In terms of overall plant material decomposability this is worth considering as mainly one tissue type in the legumes

seems to be affected by lignification.

Lignin content in plant materials varies widely, increasing with maturation and senescence. The concentration of lignin in fresh leaves ranges from 5 to 20% while that of senescent litter ranges from 10 to 40% (Palm et al., 1997; Palm and Rowland, 1997). Cereal and legume straw and litter from annual crops usually contain less than 10-15% lignin (Heal et al., 1997). It has been suggested that if the concentration of lignin exceeds 15% of plant material decomposition is reduced (Chesson, 1997).

The ratio of lignin to N (lignin:N) is sometimes used as a plant material characteristic. The decomposition of needle litter is strongly related to its lignin and N concentration (Berg et al., 1982; Palm and Rowland, 1997). When the concentration of lignin increases, or the concentration of N decreases, both the rate of decomposition and net N mineralisation decrease (Müller et al., 1988). The lignin:N ratio may serve as a good indicator of C availability to microbial degradation when the C:N ratio of the plant material exceeds 75. A high C:N ratio is often accompanied by a high lignin concentration modifying the decomposability of the plant material (Heal et al., 1997; Palm et al., 1997; Palm and Rowland, 1997). However, many of the plant materials used as green manures, catch crops or crop residues incorporated in soil are relatively low in lignin and more or less high in N, which is why these characteristics do not facilitate understanding or help in estimating their decomposition pattern.

Phenolic substances other than lignin include a range of compounds, such as tannins. Phenols can serve as a C substrate (Martin and Haider, 1986). However, many of these substances, especially tannins, can also hinder the growth or function of the decomposer organisms by binding to enzymes or making N unavailable by chemically binding to protein (Palm and Rowland, 1997). Phenols are common in tropical forage but are also found in relatively large amounts (*ca* 2% of plant material) in temperate legume forage, e.g. *Lotus spp.*

Several studies have shown that soluble phenols slow down the rate of N mineralization during decomposition but not necessary the mineralization of C (Palm and Sanchez, 1991; Handayanto et al., 1994; Constantinides and Fownes, 1994a; Handayanto et al., 1997a). In addition, phenols are believed to increase the formation of recalcitrant soil N and organic matter formation in both the long and short term.

Therefore, it has been suggested that the concentration of soluble phenols or the phenol-to-N ratio may be an important indicator for describing plant material composition (Heal et al., 1997; Palm and Rowland, 1997). However, the cited studies were conducted under tropical conditions with tropical plant species containing in general higher concentrations of phenols than temperate legumes and grasses.

Nevertheless, it has been shown that the presence of phenols in the temperate legume, birdfoot trefoil (*Lotus corniculatus),* reduced the plant protein degradation rate in the rumen (Min et al., 2001), thus specific consideration of phenols may be of importance, at least for some species.

Lipids are a heterogeneous group of fats and fatlike substances that occur in plants whereof cutin and suberin are insoluble lipid polymers that are structural components of many plant cell walls. In general the concentrations of these components, e.g. phenols, lipids, cutin and suberin, are rather small in proportion to the other more abundant components, e.g. carbohydrates and proteins (Haynes, 1986).

2.5.2.3 Moisture, temperature and soil characteristics

Climate, particularly temperature and moisture, and litter substrate quality are considered the most important to the decomposition, at least on a regional to global scale (Meetenmeyer, 1978; Donnelly et al., 1990; Vitousek et al., 1994). The oxygen level, temperature and moisture in soil may be significantly different at different depth. Surface horizons, at a depth of 5 cm, are relatively more exposed and affected by water deficits and drying-wetting and freezing-thawing cycles than deeper horizons (Rovira and Vallejo, 1997). If the plant material is incorporated deeper, both the moisture and temperature conditions in the soil are more even and the decomposition may proceed more evenly than on the surface.

On a more localized level, additional site-specific factors, such as soil texture, soil moisture, oxygen availability, pH, and the types of decomposer communities can influence decay dynamics (Howarth and Hobbie, 1982; Smith, 1982; Cornejo et al., 1994). Soil nitrogen and phosphorus availability may also influence decay dynamics directly by supplementing microbial nutrition, or indirectly through influences on substrate quality (Melillo et al., 1982; Hunt et al., 1988).

2.5.2.4 Placement of organic residues in soil

Incorporation of a plant material increases the amount of soil organic matter, which has several beneficial effects such as improved soil structure, water-infiltration capacity and water-holding capacity while reducing the risk of erosion (Swift et al., 1979; Tisdale et al., 1999). A green manure crop stimulates the activity of soil microflora and fauna, which may affect soil aggregation and stabilisation (Broersma et al., 1997; Nilson et al., 2000).

Pretreating of the plant material by cutting it into small pieces prior to incorporation also makes it possible to manipulate the decomposition and mineralization (Jensen, 1994). The decomposition rate is positively correlated to a decreasing particle size of the plant material (Wilson, 1993; Jensen, 2000). Small particles offer a relatively larger surface area, which increase the possibilities for microbial attack and activity. Moreover, smaller particle sizes also result in higher levels of soluble organic C and N. The increased availability of soluble components will lead to a more extensive microbial assimilation of both C and N (Ambus and Jensen, 1997; Rovira and Vallejo, 1997). These can favor the temporary stabilization of N added through the plant material. For example, the reduction of N leaching by incorporation of straw in the autumn was improved when the straw material had a smaller particle size (Ambus et al., 2001). In contrast, a large particle size will further delay the decomposition of recalcitrant plant components.

The spatial distribution determines the availability of the incorporated plant materials to the decomposers. By combining a fine particle size with a thorough incorporation of a plant material, such as straw, to soil, the rate of N immobilization will be maximized. If the plant material is not evenly distributed in the soil "cold and hot decomposition spots" may occur in which the rate of N immobilization may differ considerably, mainly depending on the level of available N at each spot (Jensen, 2000; Hesselsøe et al., 2001). In addition, the distance between hot spots and cold spots also affects the competition between plant roots and microorganisms for mineralized N. Wang and Bakken (1997) found that if the distance between incorporated N-rich and N-poor plant residues exceeds 6 mm, plant roots outcompete the microorganisms more or less completely.

2.5.3 Methods for studying organic residue decomposition

2.5.3.1 Mass and nutrient losses estimated by litter bag technique

The litter bag technique has been used most often for studying residue decomposition in the field, because of its simple, easily replicable, non-destructive character and its ability to exclude certain classes of soil fauna (Vanlauwe et al., 1997a). Ingrowth of microbial biomass and the transport of nutrients into the litter, result in the movement of mass into the litter that was not there originally. Thus what is often called "litter mass loss" or " decomposition" is a net mass loss although the ingrowth of mycelium normally is negligible from the point of view of mass (Berg and McClaughtery, 2003). Transport of particulates by fauna, translocation by fungi and leaching by water bring different organic fractions into environment different from that of the parent resource (Heal et al., 1997).

Many studies investigated mass and nutrient loss from organic residue by litter bag technique (McDonagh et al., 1995b; Promsakha Na Sakonnakhon et al., 2005). However, two problems associated with this technique may cause bias in relating residue N release from litterbags with its availability for the crops. Firstly, confining the residues surely alters the microclimate in the bag and the soil residue contact. Secondly, N released from litter bags is not necessary available, but may have been reimmobilized by soil microorganisms or enter the soil litter pool (Vanlauwe et al., 1997a and 1997b). Microclimatic effects of litter bags, and the use of single species of litter rather than natural mixtures are further limitations in field use (Heal et al., 1997).

Pattern of mass loss, nutrient dynamics, and decomposer associations are complex when litters from several species are mixed together. Nevertheless, observed dynamics of decomposition in litter mixtures are usually compared to predictions of mass loss, nutrient concentration change or decomposer abundance and activity calculated from measured changes in these parameters for each component litter decaying alone. Characteristics of decomposition in residue mixtures that deviated from responses predicted from decomposition of individual components alone were designated 'non-additive' (Gartner and Cardon, 2004).

The mesh size used to construct litterbags is a concern often discussed in

single-species decomposition experiments. Mesh size also will have an effect on decay rates and likely, the amount of interaction among leaves in mixed litter bags. Small mesh size could limit access to the litter by larger decomposers and, for example, chemical interactions among litters (Nilsson et al., 1999). Larger mesh size allows more access to the surrounding natural decomposer community (Health et al., 1964), but litter fragments are also more likely to be lost during sample handling before returning to the laboratory. Differences between the mass loss of the same litter under identical climate conditions but at different sites are normally minor (McClaughtery et al., 1985) with the exception of the alder forest investigated in this study. Wachendorf et al. (1997) found that the bags with a mesh size of 0.02 mm resulted in both mesofaunal and macrofaunal exclusion, whereas a mesh size of 5 mm included all soil organisms involving in the decomposition process. Small differences between the 5 and 0.02 mm mesh bags occurred at a dry site, whereas large differences were found at a wet site. At the end of a one year experiment, C losses of litter were more contributed by the activity of the fauna at the wet site than at the dry site. The higher C loss of litter at the wet site was thus mainly due to greater influence of the fauna on the breakdown process. Nevertheless, examination of the fauna in the litter bags proved that the faunal biomass in the litter bags was greater at the dry site, whereas the biomass of fauna sampled directly from soil, mainly earthworms and diptera larvae, was greater at the wet site. Fauna induced C loss at the wet site was primarily due to a higher percentage of soil organisms sampled directly from the soil, feeding on the litter in the litter bags. The high consumption of litter by soil fauna at the wet site means that little substrate remained for the litter fauna (Wachendorf et al., 1997).

2.5.3.2 Measurement of carbon dioxide evolution

Because of the complex nature of organic remains, numerous species of microorganisms are involved in the decay process. Some of C is converted to CO_2, some is incorporated into microbial tissue, and some is converted into stable humus. Several stages can be delineated in the decay of organic remains in soil. The initial phase of microbial attack is characterized by rapid loss of rapidly decomposable organic substances. In subsequent phase, organics intermediates and newly formed

biomass tissue are attacked by wide varieties of microorganisms, with production of new biomass and further C loss as CO_2. The final stage of decomposition is characterized by gradual decomposition of the more resistant plant parts, such as lignin, for which the actinomycetes and fungi play a major role (Stevenson, 1986).

During aerobic degradation the end products in the energy-yielding reactions are CO_2 and water. As a consequence, CO_2 evolution can be used as a measure of microbial activity and amounts decomposed, although part of the decomposed substrate is also used for microbial synthesis (Marstorp, 1997). However, the complete mineralization of organic matter in anaerobic environments where sulphate and nitrate concentrations are low occurs through methanogenic fermentation, which produces methane (CH_4) and CO_2 (Le Mer and Roger, 2001).

Measuring microbial activity is complex under anaerobic conditions. Fermentation products and CH_4 produced within anaerobic microsites can diffuse to aerobic areas, where oxidation to CO_2 and H_2O can occur. Microbial respiration is determined by measuring either the release of CO_2 or the uptake of O_2. Because the atmospheric CO_2 concentration is only 0.036%, versus 20% for O_2, measurement of CO_2 production is more sensitive than those for O_2 (Kandeler, 2007). The traditional manner of following the decomposition of plant residues in soil has been to measure the loss of C (as CO_2) from soil and plant residues incubated together and to subtract from this the loss of C from soil incubated in the absent of residues (Stevenson, 1986). However, observed CO_2 production from mixed residues may be different from that predicted from single residues as Gartner and Cardon (2004) found the amount of CO_2 production from mixed differed from single species litter in 65% of all mixture examined. The deviation was 2-134% from expected amounts.

2.6 N mineralization and immobilization

2.6.1 Mineralization and immobilization turnover in soils

Soil organic matter is continuously decomposed by a range of soil microorganisms including bacteria, fungi and their predators resulting in release of ammonium (NH_4^+) (mineralization). This may be oxidized to nitrate (NO_3^-) by bacterial species belonging to the genera *Nitrosospira*, which convert NH_4^+ to nitrite,

and *Nitrobacter*, which complete the oxidation to NO_3^- (nitrification). Microbial N immobilization, i.e. the assimilation of mineral N into microbial biomass, is usually concurrent to the release of mineral N. NH_4^+ is preferentially immobilized compared to NO_3^- (Jansson, 1958; Recous et al., 1990), but NO_3^- immobilization may dominate when NH_4^+ is limited (Azam et al., 1986; Rice and Tiedje, 1989; Recous et al., 1990), as it is often the case in arable soils.

The net outcome of mineralization and immobilization determines the amount of available crop N hence neither should be considered separately. Together, these processes have been referred to as the 'Mineralization-Immobilization Turnover' (MIT) (Jansson and Persson, 1982). The soil microbial biomass mediates between mineralization and immobilization and it is therefore a key factor in MIT. Even though soil microbial biomass N is only a small part, approx. 4-6% of total soil organic N (Paul, 1984), it is clear from the above why it has been referred to as 'the eye of the needle' (Jenkinson, 1990).

In addition to MIT, there may be direct microbial assimilation of soluble, low-molecular-weight, nitrogenous organic compounds such as amino acids (Hadas et al., 1987; Barak et al., 1990; Drury et al., 1991; Barraclough, 1997; Hodge et al., 2000). These two pathways are concurrent and direct assimilation of simple amino acids may be of similar magnitude compared to MIT (Barraclough, 1997; Gibbs and Barraclough, 1998; O'Dowd et al., 1999).

Mineralization of soil organic matter provides C (energy) for microbial maintenance and growth. Net immobilization of N occurs when organic matter undergoing microbial decomposition has an N content that is insufficient to meet the N demand of the microorganisms. Thus, the net outcome in terms of available crop N, i.e. net N mineralization or net N immobilization is largely determined by the C:N ratio of the organic matter undergoing decomposition (Paul and Juma, 1981; Van Veen et al., 1984; Chaussod et al., 1988). A well-known example is the net N immobilization of mineral N in arable soils that occurs after the addition of fresh N-poor crop residues such as straw (Ocio et al., 1991). It is less well known how much N immobilization occurs during the decomposition of older, more stabilized soil organic matter because the quality, i.e. the C:N ratio of the decomposing material is rarely known. The C:N ratio of the entire soil organic matter pool is often too low for

any net N immobilization to occur, but density fractionation of soil organic matter (e.g. Golchin et al., 1998) reveals that soil organic matter is not a homogenous pool but contains fractions of distinctly different C:N ratios. Studies in a range of ecosystems highlighted that N mineralization may be accompanied by substantial N immobilization (Davidson et al., 1992; Ledgard et al., 1998; Murphy et al., 2003).

Carbon and N cycles in soil are strongly linked due to the simultaneous uptake, i.e. assimilation, of C and N by the decomposing microflora. The fraction of consumed C that is converted to microbial biomass C varies widely depending on differences in substrate quality, e.g. ratio between C and N (C:N), molecular complexity, and availability of inorganic nutrients, especially N (Bloem et al., 1997). The C flow and the C/N ratio of the decomposers determine the requirements for microbial assimilation of N (Mary et al., 1993).

Mineralization occurs when inorganic forms of an element are released during catabolism of organic resources, e.g. CO_2 from carbohydrates, and NH_4^+ from organic N components. The consequence of catabolism is the release of energy for anabolic activity that also involves the uptake and use of nutrients, i.e. assimilation. The NH_4^+ ions are subsequently converted through oxidation to NO_3^-. The process whereby NH_4^+ is oxidized to NO_3^-, referred to as nitrification, is mediated by autotrophic nitrifying bacteria such as *Nitrosomonas* and *Nitrobacter* (Stevenson and Cole, 1999; Benbi and Richer, 2002). N is then transformed back into organic N through microbial assimilation or plant uptake. Through these processes N is immobilized into a form that is temporarily unavailable to other organisms. Immobilization and mineralization always accompany each other operating in the reverse directions. Immobilized N is sooner or later re-mineralized due to the turnover of plant material and the decomposer community. The amount of mineral N resulting from the mineralization and immobilization processes corresponds to the net N mineralization, equaling the extent to which mineralization exceeds immobilization.

However, it is very difficult to optimize N delivery from decomposing plant materials to meet crop N demand. Nitrogen in organic materials can be mineralized at times when little or no crop uptake is taking place leading to increased leaching of mineral N (Jensen, 1994; Myers et al., 1994). Conversely, N deficiency will occur if N uptake exceeds the N mineralization rate. In addition, crops take up around 5 – 50%

of the green manure N during the subsequent growing season (Ladd and Amato, 1986; Jensen, 1994). While the rest is either lost through volatilization or leaching, or is immobilized in soil organic matter, from where some of it is stabilized into humic substances.

2.6.2 Quantification of gross N processes

Mineralization, nitrification and immobilization continuously affect the amounts of mineral N over time. The amount of mineral N at a certain time is therefore only a snapshot of the net balance between these N processes (ignoring other N losses, e.g. denitrification, nitrate leaching or crop N uptake from the mineral N pool). A low rate of net N mineralization may not always be the result of a low rate of gross N mineralization, but may equally well be the result of a high rate of immobilization from the mineral N pool. Because gross N processes describe the total production of NH_4^+ and NO_3^- (gross mineralization and nitrification) and assimilation (gross immobilization) and not just the net balance between these processes, quantification of these processes is essential to our understanding of the turnover of mineral N in soils.

Gross N processes are studied using the ^{15}N isotope dilution technique. ^{15}N is a stable isotope of nitrogen with mass number 15. Gross N mineralization, for example, is estimated by enriching the NH_4^+ pool with ^{15}N and measuring the changes of the NH_4^+ pool size and dilution of ^{15}N in the NH_4^+ pool over time. The ^{15}N enriched NH_4^+ pool is diluted due to introduction of NH_4^+ at natural abundance, i.e. NH_4^+ with natural background concentration of ^{15}N (0.3663 atom% ^{15}N), *via* mineralization from soil organic matter. Gross nitrification is similarly estimated; the difference being that the NO_3^- pool is enriched with ^{15}N and the changes of the NO_3^- pool size and dilution of ^{15}N in the NO_3^- pool are measured over time. In this case, the ^{15}N enriched NO_3^- pool is diluted due to introduction of NO_3^- at natural abundance *via* mineralization from soil organic matter followed by nitrification from the NH_4^+ pool.

The ^{15}N isotope dilution technique (Kirkham and Bartholomew, 1954) can be used for determining gross mineralization, nitrification and immobilization rates in soils. The technique is based on several assumptions, namely, (1) no isotopic

discrimination, (2) no re-mineralization of added labelled N, (3) all rate processes are constant during the incubation period and (4) equilibrium and identical behavior between added and native N pools. Isotope pool dilution techniques enable gross rates of nitrification (or mineralization) to be determined by monitoring the decline in the ^{15}N abundance in a nitrate or ammonium pool, labelled at t=0, and receiving unlabelled nitrogen via nitrification or mineralization, respectively (Murphy et al., 2003). Labelled N can be applied as $^{15}NH_4^+$ solution or injected as $^{15}NH_3$ gas into a soil. The use of ^{15}N pool dilution and enrichment can also be used to separate the heterotrophic and autotrophic pathways of nitrification (Kandeler, 2007). Moreover, the ^{15}N isotope dilution technique is a promising means to analyze the N fluxes in soil where organic matter is applied (Shindo and Nishio, 2005). The gross rates of N transformation were also determined employing this technique for the soils applied with green manure (Andersen and Jensen, 2001), wheat straw (Recous et al., 1999).

2.7 Manipulation of decomposition and N release from organic residues for the purpose of synchronization of N release and plant demand

Crop residues decomposition depends greatly on their chemical compositions such as C: N ratio, polyphenol and lignin contents. It was found that those residues with high of such contents decomposed slowly while those low contents decomposed faster. Decomposition of crop residues can be manipulated as follows.

2.7.1 Crop residue application methods

Residues can be manipulated either by mulching or incorporation. Mulching reduces the contact between residues and soil as compared to incorporation. This may affect the decomposition dynamics. Residue management practices that involve intensive tillage and incorporation of residues increase residue decomposition rates and loss of soil organic matter. It is difficult to distinguish the effect derived from residue incorporation from tillage because incorporation is accomplished through some types of tillage operation (Gesch et al., 2007). Decomposition rates of incorporated residue is faster than those of surface mulched residues, resulting from greater soil-residue contact, a more favorable and stable micro-environment,

particularly soil moisture regime, and increased availability of exogenous N for decomposition by microorganisms (Cogle et al., 1987; Schomberg et al., 1994). Important secondary effects of tillage on the soil microclimate include the influence of surface residue coverage on soil temperature, water interception and infiltration, and the effects of tillage induced changes in porosity and the effect of soil structure on soil aeration and water relations (Yadvinder-Singh et al., 2005). The depth of residue incorporation was shown to affect the decomposition of residues. Kanal (1995) reported that the increasing depth of residue incorporation from 50-200 mm resulted in a decrease in breakdown rate due to less biological activity. Likewise, the study of Beri et al, (1992) indicated that the decomposition rate of rice straw was reduced by 13% by increasing the depth of incorporation of residues from 0-10 cm to 20-30 cm.

2.7.2 Application of labile C

The availability of labile C to decomposer organisms is the main determinant of the overall rate of decomposition of plant residues. There are a number of reports studied on the interactions between labile and resistant C compounds during decomposition. For example, Hamer and Marschner (2002) found that the *in vitro* decomposition of lignin was enhanced in the presence of glucose and Vanlauwe et al. (1994) found that the *in vivo* decomposition of the cell wall fraction of maize (*Zea may* L.) and native soil organic matter were enhanced in the presence of maize soluble C compounds. Many experiments in which the decomposition of soil organic matter was stimulated by the addition of labile or moderately labile C containing compound such as glucose (Degens and Sparling, 1996; Falchini et al., 2003), cellulose (Fontaine et al., 2004), roots and root mucilage (Mary et al., 1993). Fontaine et al. (2004) demonstrated that the addition of cellulose to Savannah soil increased the decomposition of native soil C by as much as 55% leading to a depletion of soil C of 174 mg kg^{-1}.

2.7.3 Application of labile N

In most cases, N availability does not increase the overall rate of decomposition of plant residues or soil organic matter. It was found that added N could stimulate (Neff et al., 2002; Wardrop and Firestone, 2004) or had undetectable

effects on (Aerts et al., 1992) the rate of decomposition of organic matter but the balance of evidence suggested that added N (exogenous) retarded the overall rate of decomposition of plant residues (Fox, 1988; Hagedorn et al., 2003). However, Fox (1988) concluded that the predominant long term result was no change or a decrease in the rate of decomposition though in some situation, the rate of decomposition was increased following the addition of N (perhaps where labile C is readily available). There were several studies indicated that added N stimulates the rate of decomposition of labile C compounds but may retard decomposition of resistant C. Fox (1988) proposed the following mechanisms by which N may inhibit the decomposition of plant residues; (i) added N disturbs the outcome of competition between potent and less potent decomposer organisms, changing patterns of microbial succession, (ii) through 'ammonia metabolite repression', N blocks the production of certain enzymes, (at least in basidiomycete fungi), and enhances breakdown of the most available cellulose causing recalcitrant lignocellulose to accumulate, and (iii) amino compounds condense with polyphenols and other decomposition products, forming the precursors of humic macromolecules, which are toxic or inhibitory to decomposers.

2.7.4 Mixed-species leaf litter

Physical, chemical and biological processes, individually or in combinations, can drive interactions among adjacent leaf litters from different species during decomposition. McArthur et al. (1994) and Hector et al.(2000) reported that mixing leaves from species with differing resource qualities and leaf structure changes the chemical environment and physically alters the total litter surface where decomposition is occurring.

Since it is usually not feasible to considerably change the quality of any given plant material, mulch or litter quality has been manipulated by mixing high- and low-quality organic matter to reduce leaching losses, prolong nutrient availability, and synchronize nutrient release with crop demands (Myers et al., 1994). It has been shown that mixing plant residues of varying quality can be used to regulate the timing of nutrient availability (Handayanto et al., 1997b; Vityakon et al., 2000). Therefore, when plant residue of different species is mixed, the decomposition of litter of low

labile C content is often stimulated by its proximity to that higher labile C content. Characteristics of decomposition in litter-mixes that deviate from responses predicted from decomposition of single-species litters alone are designated "non-additive"; "additive" responses in mixes are predictable from component species decaying alone (Gartner and Cardon, 2004). Gartner and Cardon (2004) found that non-additive patterns of mass loss were observed in 67% of tested mixtures; mass loss is often (though not always) increased when litter of different species are mixed. Positive non-additive interactions are often observed when plant residue of low C:N ratio decomposes in mixture with high C:N ratio. For example, Prescott (1996) demonstrated that high C:N residue of paper birch (*Betula papyrifera* Marsh) lost mass more rapidly when incubated with low C:N residue of red alder (*Alnus rubra* Bong) than when incubated with high C:N residue of Douglas fir (*Presudotsuga menziesii* Mirb) or lodgepole pine (*Pinus contorta* Dougl). One mechanism that might explain the occurrence of positive non-additive effects when plant litter decomposes in mixtures is that the differential concentrations of nutrients allows translocation of nutrients between the litter types, enabling more efficient utilization of C substrates by microorganisms (McTiernan et al., 1997). Considering the conclusion that initial litter N usually retards overall decomposition (Berg and Meentemeyer, 2002), it is reasonable to think that only short term positive effects observed in mixtures might be related to increase availability of N. Support for this view is provided by Smith and Bradford (2003) who mixed grass litters that differed in initial N concentration but not species or structural plant part identity and observed negative effects on decomposition.

2.7.5 Increased available soil moisture

Mineralization rate of N in crop residues is reduced at low soil water content (Yadvinder-Singh et al., 2005). Under field conditions, soil moisture condition may change from time to time and this may cause the shifting participation of different microorganisms during plant residue decomposition (Parmelee et al., 1989). Additionally, soil moisture could alter the competition for N between plants and soil microorganisms (Lodge et al., 1994; Lipson and Monson, 1998). It could affect aggregate stability (Lavee et al., 1996), the intensity of drying–rewetting cycles, and

root exudation (Gorissen et al., 2004). Dijkstra and Cheng (2007) found that root exudation of labile C may also become more effective in stimulating microbial decomposition in the higher soil moisture and indicate that moisture conditions significantly modulate rhizosphere effects on SOM decomposition. An increase in soil C decomposition in the presence of plants may also occur because of intensified drying-rewetting cycles in the soil (Lundquist et al., 1999). Dry-rewetting cycles could enhance solubility of non-living soil organic matter (Van Gestel et al., 1993), increase microbial death during dessication and osmoregulatory shock (Magid et al., 1999) and increase deterioration of soil aggregates (Van Veen and Kuikman, 1990).