Modelling Pasture-based Automatic Milking System Herds: Grazeable Forage Options

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ABSTRACT: One of the challenges to increase milk production in a large pasture-based herd with an automatic milking system (AMS) is to grow forages within a 1-km radius, as increases in walking distance increases milking interval and reduces yield. The main objective of this study was to explore sustainable forage option technologies that can supply high amount of grazeable forages for AMS herds using the Agricultural Production Systems Simulator (APSIM) model. Three different basic simulation scenarios (with irrigation) were carried out using forage crops (namely maize, soybean and sorghum) for the spring-summer period. Subsequent crops in the three scenarios were forage rape over-sown with ryegrass. Each individual simulation was run using actual climatic records for the period from 1990 to 2010. Simulated highest forage yields in maize, soybean and sorghum- (each followed by forage rape-ryegrass) based rotations were 28.2, 22.9, and 19.3 t dry matter/ha, respectively. The simulations suggested that the irrigation requirement could increase by up to 18%, 16%, and 17% respectively in those rotations in El-Niño years compared to neutral years. On the other hand, irrigation requirement could increase by up to 25%, 23%, and 32% in maize, soybean and sorghum based rotations in El-Nino years compared to La-Nina years. However, irrigation requirement could decrease by up to 8%, 7%, and 13% in maize, soybean and sorghum based rotations in La-Nina years compared to neutral years. The major implication of this study is that APSIM models have potentials in devising preferred forage options to maximise grazeable forage yield which may create the opportunity to grow more forage in small areas around the AMS which in turn will minimise walking distance and milking interval and thus increase milk production. Our analyses also suggest that simulation analysis may provide decision support during climatic uncertainty. (Key Words: Automatic Milking System, Agricultural Production Systems Simulator, Dairy, Forage Options, Forage Rotations)

INTRODUCTION

Previous research conducted at Camden, NSW, Australia over two years showed that the software modelling framework, Agricultural Production Systems Simulator (APSIM) can be used effectively to simulate and validate yield and nutrient-use efficiencies of an annual cycle of a triple-crop complementary forage rotation (CFR) of maize (grown for silage), forage rape and field peas (Islam and Garcia, 2010). Many researchers (Carberry et al., 1996; Chauhan, 2010) also reported that modelling approaches can assist in arriving at initial estimates of various productive parameters of crops or crops in rotations based on historic climate data and soil characteristics without having to conduct expensive field experiments. These evidences indicate that new research questions can be tested using APSIM or that various treatment options can be screened to prioritize treatments for field experiments. Thus there is a good prospect of APSIM to be used as a tool to screen forage options that can supply grazeable forages for a large herd (400 to 800 cows) throughout the year in an automatic milking system (AMS) dairy.

Pasture-based AMS systems generally have larger herds which pose unique challenges to AMS (Jago et al., 2007) compared to herds housed indoors. Jago et al. (2004) and Jago and Kerrisk (2011) reported that the long walking distances associated with pasture-based large herds milked with AMS reduces cow trafficking and milking frequency. The potential exists to minimize average walking distances if the volume of grazeable forages grown in close vicinity to...
the dairy is increased. Incorporation of principles of a complementary forage system (Farina et al., 2011) and high yielding forages may provide an opportunity to grow more feed in a small area compared to traditional pastures (e.g., 17 t dry matter [DM/ha] (Garcia et al., 2007a) thereby reducing average walking distances. Analysis of two years of historical data from a pasture-based AMS research herd has indicated the number of extended milking intervals (>16 h intervals between consecutive milkings) was increased when cows were grazing paddocks in excess of 800 m from the dairy. The extended milking intervals were also associated with a reduced milk accumulation rate in the udder (Lyons et al., 2014).

Recent developments with AMS technology have resulted in installation, testing and co-development of a prototype robotic rotary (RR; Automatic Milking Rotary, DeLaval AMR, Tumba, Sweden) which is expected to have the capacity to milk up to 800 cows when it is commercialized (Kolbach et al., 2012). The RR has the potential to be used with either batch milking or voluntary cow traffic. If the RR is to be used with voluntary cow traffic, it will likely be adopted with herds much larger in size than any existing pasture-based AMS. With the imminent commercialization of the RR (DeLaval AMR, Sweden) it is important for research to address some of the potential challenges that may be associated with voluntary trafficking of large pasture-based herds. One of those challenges is the longer distances to pasture that will be inevitable with the larger herds. Developing robust management practices within an AMS system is important to ensure that farmers have the best opportunity to be successful when AMS is adopted on-farm (Donohue et al., 2010). One approach is to increase the amount of grazeable forages within a 1-km radius of the dairy.

Strategic selection of high yielding grazeable forages in different seasons that have high growth and/or re-growth potential in summer (e.g., maize, soybean, sorghum) or in autumn-winter (e.g., forage rape, ryegrass) has the potential to dramatically increase the yield of forages compared to current levels of pasture utilization (14 to 20 t DM/ha; Stockdale, 1983; Garcia et al., 2007b). Previous research has shown that sowing soybean in late-spring and forage rape in late-summer may provide 8 to 10 t DM/ha (Islam and Garcia, unpubl. results) and 11 to 14 t DM/ha (Garcia et al., 2008; Islam and Garcia, 2012; Islam et al., 2012a) respectively in three harvests. Ryegrass (short season) can also provide 13 to 14 t DM/ha in 7 to 8 harvests (Neal et al., 2009). However, yield of these forages and water requirements may vary due to climatic variations such as El-Nino Southern Oscillation (ENSO) events (Chauhan, 2010) which need to be investigated. It was hypothesized that using these forages in rotations individually, or by intercropping or over-sowing may increase grazeable forage supply for AMS herds substantially. Various work reported advantages of intercropping in terms of yield, nutrient-use efficiency and in controlling weeds, pests and diseases (Ofori and Stern, 1987; Caviglia et al., 2004).

Therefore, a modelling study was undertaken in order to investigate the potentials of APSIM to screen forages that can be grown to supply a high yield of grazeable forages for large AMS herds. The expected output of this study was to gather information on different options of forage crops for AMS farms potential yield and optimum growing season of such forages and alleviate risks. The main objective of this APSIM modelling was to develop sustainable forage option technologies tailored to AMS dairy farming systems.

**MATERIALS AND METHODS**

**Simulation model**

The model used in this study (APSIM version 7.0) is a crop simulation model (Keating et al., 2003) consisting of modules that incorporate aspects of soil nitrogen (N), water, crop residues, crop growth and development, and their interactions within a cropping system that is driven by daily weather data. It calculates the potential yield, which is the maximum yield reached by a crop in a given environment that is not limited by pests, diseases, frost damage, weeds and lodging, but is limited by temperature, solar radiation, N and water supply (Asseng et al., 2008). The model is calibrated, tested and validated in different locations and is extensively used in Australia and internationally (Robertson et al., 2005; Anwar et al., 2009; Chauhan, 2010; Pemberton et al., 2011) to simulate yield of many grain and forage crops individually and in rotations with various input rates for N and water under various sowing management strategies. The above mentioned publications reported their assessed model predictions against field trials using a range of soil, crop, climatic and management data and have concluded that the APSIM model is able to adequately simulate crops and forages growth. More recently, the capability of the model to simulate triple-crop annual rotations has been confirmed (Islam and Garcia, 2010).

**Site, soil and climate**

The chosen study site was Camden, located (150.70°E, -34.05°S) in New South Wales, Australia. Camden is the location of Australia’s first and only pasture-based AMS research herd. Annual average rainfall of this site was 737.7 mm (1900 to 2010), with a diverse annual range from 324 (1944) to 1,542 mm (1950). Rainfall is generally quite evenly dispersed through the 12-month period. On average, rainfall in spring (September to November), summer (December to February), autumn (March to May) and winter (June to August) accounted for 24.1%, 27.8%, 20.8%, and 28.6% of the annual rainfall, respectively. Mean annual
Simulations were conducted using the APSIM model with historical weather data from 1900 to 2010, which was downloaded from the enhanced climate database SILO (www.longpaddock.qld.gov.au/silo). The model used inputs of minimum and maximum temperatures, rainfall, solar radiation and vapour pressure deficit on a daily time step every year to simulate growth and yield of forages used in the rotation. The soil of the site corresponded to brown chromosols and black vertisol (Isbell, 2015). Thus, a total of 300 kg N/ha was applied to forage rape. On after each subsequent grazing (Islam and Garcia, 2012).

Table 1. Soil properties at the Camden study site used in simulation modules in APSIM

| Depth (cm) | BD (g/cc) | SAT (mm/mm) | DUL (mm/mm) | AirDry (mm/mm) | LL (mm/mm) | PAWC (mm) | Organic carbon (%) | pH (water) | SW (%) | NO₃-N (kg/ha) |
|-----------|-----------|-------------|-------------|----------------|------------|-----------|-------------------|------------|--------|---------------|
| 0 to 15   | 1.29      | 0.48        | 0.29        | 0.05           | 0.10       | 29.7      | 1.37              | 6.3        | 9.5    | 0.19          |
| 15 to 30  | 1.63      | 0.36        | 0.29        | 0.12           | 0.16       | 20.6      | 0.43              | 6.3        | 15.5   | 0.24          |
| 30 to 60  | 1.40      | 0.44        | 0.39        | 0.24           | 0.24       | 46.2      | 0.33              | 6.8        | 23.8   | 0.42          |
| 60 to 90  | 1.44      | 0.43        | 0.38        | 0.23           | 0.23       | 44.7      | 0.24              | 7.7        | 22.8   | 0.43          |
| 90 to 120 | 1.55      | 0.39        | 0.34        | 0.23           | 0.23       | 33.0      | 0.15              | 8.2        | 22.7   | 0.46          |
| 120 to 150| 1.68      | 0.34        | 0.29        | 0.21           | 0.21       | 23.7      | 0.11              | 8.3        | 20.9   | 0.50          |
| 150 to 180| 1.72      | 0.32        | 0.27        | 0.21           | 0.21       | 18.6      | 0.11              | 8.2        | 21.0   | 0.52          |

APSIM, Agricultural Production Systems Simulator; BD, bulk density; SAT, saturated water content; DUL, drained upper limit of soil water content; LL, lower limit of soil water content; PAWC, plant available water capacity; SW, soil water; NO₃-N, nitrate-nitrogen.

Minimum and maximum temperature were 10.7°C and 23.3°C, respectively and mean average radiation was 16.9 MJ/m².

Simulation scenarios and model criteria

The aim of this study was to investigate and identify forage crops options with regard to their suitability for AMS herds through APSIM simulations. These crop rotations were intended as potential options that may provide forages throughout the year and enable field researchers to make tailored decisions on which forage option(s) may be suitable for AMS herds.

In order to investigate impact of different forage options that can supply maximum forages to AMS herds throughout the year, three main rotational forage options simulations were carried out. These were: i) maize, ii) soybean, and iii) sorghum as summer forages each followed by forage rape over-sown or cropped with ryegrass to complete a year-round rotation. There are no existing modules to simulate forage rape and ryegrass using APSIM. However, previous work (Islam and Garcia, 2010) have indicated that the canola and weed modules of APSIM can closely simulate yields of forage rape and ryegrass, respectively. Whilst Sorghum does exist in the APSIM module, its simulated regrowth is limited. However, it was found that SweetSorghum modules in APSIM simulations generate regrowth, which was more representative of re-growth achieved in the field. As a result the modules of APSIM maize, canola, weed and SweetSorghum were used to simulate yields of maize, forage rape, ryegrass and sorghum, respectively.

Each of the forage crops were simulated over the years from 1900 to 2010. Long term average values of monthly simulated growth rate (kg/ha/d) for each forage in the rotation were used to calculate total simulated yield. Risks associated with ENSO events particularly due to El-Nino were also assessed. Data dispersion among years or differences due to climate was used for risk assessment or probability of not achieving a certain target.

Irrigation was non-limiting in all simulations and efficiency of irrigation was set at 1. Initial surface residue was set at 1,000 kg/ha and carbon:nitrogen (C:N) ratio of initial residue was 80. Details of agronomic principles used in each of the three rotation simulations are provided below and presented in Table 2 and 3.

Maize followed with forage rape and ryegrass (over-sown with forage rape): Maize was sown in simulations in four different sowing dates with a fixed rate N fertilizer (135 kg/ha) applied at the time of sowing. Simulated sowing dates were 10 October, 20 October, 20 November and 20 December. All maize crop sowing treatments were grazed (harvested in simulations) at Zadoks growth scale 8 (Zadoks et al., 1974). After the final grazing of maize, forage rape was sown respectively in maize sowing treatments on 15 February, 20 February, 28 February and 7 March in the four maize sowing treatments respectively. Ryegrass was over-sown with forage rape immediately after first grazing and second grazing simulations respectively after first two and last two sowing dates (Table 2). Final grazing of forage rape in all simulations occurred on 13 August to allow high growth of ryegrass. Forage rape was grazed when simulated yield reached 4.5 t/ha or over. Three to four grazings were achieved from forage rape. A total of 70 kg N/ha was applied to forage rape at the time of sowing, 90 kg N/ha after the 1st grazing and 70 kg N/ha thereafter after each subsequent grazing (Islam and Garcia, 2012). Thus, a total of 300 kg N/ha was applied for forage rape. On
Table 2. Sowing dates and rates of N fertiliser and harvesting dates of forages in the rotations used in simulations

| Simulations | Sowing date | N application (A) timing and rate (kg/ha) | Harvest |
|-------------|-------------|------------------------------------------|---------|
|             |             | Summer forage                             | A1 | A2 | A3 | Harvest | Autumn-winter-spring forage                            | A1 | A2 | A3 | A4 | Harvest |
|             |             | Forage rape                               | Rate | Rate | Rate | Rate | Ryegrass | Rate | Rate | Rate | Rate | Rate | Rate | Rate | Rate | Rate | Rate | Rate |
| M1          | 10-Oct      | 15-Feb                                    | 1-20 | 27-45 | 30-60 | 30-60 | 14-Feb | 15-Feb | 16-Feb | 70 | 26-70 | 26-70 | 26-70 | 13-Aug | 9-Oct | 435 |
| M2          | 20-Oct      | 20-Feb                                    | 1-20 | 27-45 | 30-60 | 30-60 | 19-Feb | 20-Feb | 21-Feb | 70 | 26-70 | 26-70 | 26-70 | 13-Aug | 19-Oct | 435 |
| M3          | 20-Nov      | 27-Feb                                    | 1-20 | 27-45 | 30-60 | 30-60 | 27-Feb | 28-Feb | 26-Jun | 70 | 26-70 | 26-70 | 26-70 | 13-Aug | 19-Nov | 435 |
| M4          | 20-Dec      | 6-Mar                                     | 1-20 | 27-45 | 30-60 | 30-60 | 13-Mar | 7-Mar | 19-Jul | 70 | 19-70 | 19-70 | 19-70 | 13-Aug | 1-Dec | 435 |
| S1          | 15-Oct      | 0                                         | 0    | 0    | 0    | 0    | 19-Feb | 20-Feb | 1-Apr  | 70 | 1-70  | 1-70  | 1-70 | 14-Oct | 14-Oct | 280 |
| S2          | 15-Nov      | 0                                         | 0    | 0    | 0    | 0    | 14-Mar | 15-Mar | 1-May  | 70 | 1-70  | 1-70  | 1-70 | 14-Oct | 14-Nov | 280 |
| S3          | 30-Nov      | 0                                         | 0    | 0    | 0    | 0    | 24-Mar | 25-Mar | 25-May | 70 | 25-70 | 25-70 | 25-70 | 14-Oct | 29-Oct | 280 |
| S4          | 15-Dec      | 0                                         | 0    | 0    | 0    | 0    | 30-Mar | 31-Mar | 31-May | 70 | 30-70 | 30-70 | 30-70 | 14-Oct | 29-Nov | 280 |
| Sg1         | 1-Nov       | 40                                        | 7-Jan | 25-Feb | 40-25-Feb | 30-Apr | 1-May  | 1-May  | 2-May  | 70 | 15-70 | 15-70 | 15-70 | 31-Oct | 31-Oct | 330 |
| Sg2         | 15-Nov      | 40                                        | 7-Jan | 25-Feb | 40-25-Feb | 40-30-Apr | 1-May  | 1-May  | 2-May  | 70 | 15-70 | 15-70 | 15-70 | 14-Nov | 14-Nov | 330 |
| Sg3         | 30-Nov      | 40                                        | 15-Jan | 25-Feb | 40-25-Feb | 40-30-Apr | 1-May  | 1-May  | 2-May  | 70 | 15-70 | 15-70 | 15-70 | 29-Nov | 29-Nov | 330 |
| Sg4         | 15-Dec      | 40                                        | 15-Jan | 25-Feb | 40-25-Feb | 0-30-Apr | 1-May  | 1-May  | 2-May  | 70 | 15-70 | 15-70 | 15-70 | 14-Dec | 14-Dec | 290 |

1. M, S, and Sg represents maize, soybean and sorghum respectively each followed by a intercrop of forage rape-ryegrass (weed) rotation and 1, 2, 3, and 4 against each of M,S, and Sg represents as sowing 1, sowing 2, sowing 2, and sowing 4 respectively.
2. Maize harvested at Zadoks growth stage 8.
3. Weed as ryegrass.
4. Forage rape harvested at pre-graze cover of ≥4.5 t DM/ha and ryegrass as weed harvested at pre-graze cover of ≥2 t DM/ha.

Table 3. Agronomy and management rules used in simulations\(^1\) during the periods from 1990 through 2010

| Parameters                 | Maize | Soybean | Sorghum as SweetSorghum | Forage rape as Canola | Ryegrass as weed |
|----------------------------|-------|---------|-------------------------|-----------------------|------------------|
| Cultivar                   | Pioneer 3527 | Davis | Sugargraze              | Early                 | Late             |
| Sowing characteristics     |       |         |                         |                       |                  |
| Plants/sq.m.               | 10    | 30      | 16                      | 80                    | 100              |
| Row spacing (cm)           | 65    | 17      | 65                      | 17                    | 17               |
| Sowing depth (cm)          | 4.5   | 3.0     | 3.0                     | 2.0                   | 1.5              |
| Harvesting                 | Zadoks scale 8 or day 59; harvest height 20 cm | When crop reached 4.5 t DM/ha; harvest height 35 cm | When crop reached 4.5 t DM/ha; harvest height 35 cm | When crop reached 4.5 t DM/ha; harvest height 35 cm | When crop reached 2 t DM/ha; harvest height 5 cm |

1. Irrigation water was non-limiting as automatic irrigation in simulation was on; efficiency of irrigation was set at 1; initial surface residue was set at 1,000 kg/ha and C:N ratio of initial residue was 80; 0.90 removed from all crops when harvested at grazing.
total of 280 kg N/ha was applied to forage rape; 70 kg N/ha at the time of sowing and 70 kg N/ha after each harvest. No N fertilizer was applied to specifically to ryegrass as it was planted as a companion to the forage rape. The grazing rules for forage rape and ryegrass were the same as described in maize rotations above. The final grazing of each of the forage rape-ryegrass was made a day before the next sowing of soybean to start the rotation again.

Sorghum followed with forage rape and ryegrass (intercropped): Sweet Sorghum was sown in simulations on four sowing dates (1 November, 15 November, 30 November and 15 December). The final grazing date of sorghum (in all sowing date simulations) was 30 April.

A fixed final grazing date applied to sorghum treatment simulations was set in recognition of the high frost risk after 30 April. The 1 November sowing date simulation achieved only two grazings whereas the optimum sowing date for the forage rape (30 April) was suited to the sorghum, it resulted in the maximum of only two grazings in simulations; 70 kg N/ha at the time of sowing and 70 kg N/ha after each sorghum grazing. Therefore, in the first three sowing treatments, N fertilizer was applied up to three times (total 280 kg N/ha) but only twice in the last sowing treatment (total 120 kg N/ha), in all treatments, N fertilizer was applied up to three times (total 280 kg N/ha) but only twice in the last sowing treatment (total 120 kg N/ha), but only twice in the last sorghum treatment (total 80 kg N/ha).

The forage rape-ryegrass was sown on 1 May in all sorghum simulations. The final grazings were carried out on 31 October, 14 November, 29 November and 14 December to coincide with the 4 sowing dates for the subsequent season of sorghum (Table 2). In all treatments, only two grazings of forage rape was possible. Nitrogen was applied at 140 kg/ha in all sowing simulations; 70 kg N/ha at the time of sowing and 70 kg N/ha after the 1st grazing of forage rape. No N fertilizer was applied directly to the ryegrass in the simulation. Grazing management of forage rape and ryegrass was the same as described for these forages in the maize and soybean rotations (see previous sections).

#### Approaches used for model validation

Local yield data of individual forages (used in rotation simulations) generated in field experiments at Camden were used to simulate the growing conditions observed in the field (Table 4). In addition, our experiences on field experiments (Garcia and Fulkerson, 2005; Garcia et al., 2006; 2007a; b; 2008; Farinha et al., 2011; Islam and Garcia, 2012) on annual cycle of a triple-crop CFR including simulations and validation of CFR using a range of N (0 to 523 kg/ha) and water (0 to 14 ML/ha) (Islam and Garcia 2010) and experimental data on triple-crop CFR rotations have created a level of confidence within the authors that APSIM is a suitable tool allowing the simulation and screening of potential grazeable forage rotations for AMS herds. However, it should be mentioned that the forage screening simulation rotations for AMS herds used in this

### Table 4. Actual and simulated data used for validation of the model

| Crop Compositions | Sowing date | Final harvest | Irrigation | N<sub>f</sub> kg/ha | Yield (t DM/ha) | Cultivars | Plants/ sq.m. | Yield (t DM/ha)<sup>1</sup> | Row spacing, m | Simulated cultivars |
|-------------------|-------------|---------------|------------|---------------------|----------------|----------|-------------|----------------------|--------------|------------------|
| Islam and Garcia (2014)<sup>a</sup> Soybean only | 19/11/2010 | 14/04/2011 | Full | 240<sup>2</sup> | 8.3 | Intrepid | 30 | 10.2 | 0.17 | Davis |
| Islam and Garcia (2014)<sup>a</sup> Soybean only | 19/11/2010 | 14/04/2011 | 0 | 240<sup>2</sup> | 5.8 | Intrepid | 30 | 7.8 | 0.17 | Davis |
| Islam and Garcia (2014)<sup>a</sup> Soybean only | 19/12/2008 | 20/02/2009 | Full | 240<sup>2</sup> | 5.1 | Intrepid | 30 | 6.2 | 0.17 | Davis |
| Islam and Garcia (2014)<sup>a</sup> Soybean only | 19/11/2010 | 14/04/2011 | Full | 240<sup>2</sup> | 7.7 | Warrigal | 30 | 10.2 | 0.17 | Davis |
| Islam and Garcia (2014)<sup>a</sup> Soybean only | 19/11/2010 | 14/04/2011 | 0 | 240<sup>2</sup> | 6.8 | Warrigal | 30 | 7.8 | 0.17 | Davis |
| Islam and Garcia (2014)<sup>a</sup> Maize only | 22/02/2009 | 23/04/2009 | Full | 101 | 5.6 | 3H50 | 13 | 4.2 | 0.65 | Pioneer 3527 |
| Islam and Garcia (2014)<sup>a</sup> Maize only | 22/02/2009 | 1/04/2010 | Full | 135 | 7.0 | 3H50 | 13 | 5.0 | 0.65 | Pioneer 3527 |
| Islam and Garcia (2014)<sup>a</sup> Maize | 22/02/2009 | 23/04/2009 | Full | 101 | 5.5 | 3H50 | 12 | 5.0 | 0.65 | Pioneer 3527 |
| Islam and Garcia (2013) Maize-Ryegrass | FR | 22/02/2009 | 24/09/2009 | Full | 300 | 12.4 | Goliath | 80 | 10.3 | 0.17 | Early (Canola) |
| Islam and Garcia (2013) Maize-Ryegrass | FR | 22/02/2009 | 23/04/2009 | Full | 101 | 5.9 | 3H50 | 12 | 4.0 | 0.65 | Pioneer 3527 |
| Islam and Garcia (2013) Maize-FR | FR | 22/02/2009 | 24/09/2009 | Full | 100 | 5.4 | Surrey | 100 | 6.6 | 0.17 | As weed (Early) |
| Islam and Garcia (2013) Maize-FR | FR | 22/02/2009 | 1/04/2010 | Full | 140 | 6.9 | 3H50 | 12 | 4.8 | 0.65 | Pioneer 3527 |
| Garcia et al. (2006)<sup>b</sup> Maize-FR-Maple pea | FR | 20/02/2004 | 24/09/2004 | Full | 270 | 11.4 | Goliath | 80 | 11.0 | 0.17 | Early (Canola) |
| Pancha and Garcia (2008)<sup>c</sup> Soybean only | 21/11/2007 | 2/02/2008 | Full | 0 | 7.9 | Intrepid | 80 | 7.5 | 0.17 | Davis |
| Horadagoda and Garcia (2011)<sup>d</sup> Soybean only | 12/12/2008 | 22/02/2009 | Full | 27 | 9.1 | Intrepid | 80 | 7.8 | 0.17 | Davis |

FR, forage rape; CFR, complementary forage rotation.
1 Every simulation covered periods from 1900 through 2010.
2 Rates of N fertilizer was the same as observed except for ryegrass which was simulated without N.
3 FR was grown in a rotation of CFR over three years.
4 DAP (Di-ammonium phosphate) contained 18% N, 20% P, and 2.2% sulphur (Hi-fert, Melbourne, Victoria).
5 Unpublished results.
study have not been tested in any field studies nor have they been reported.

RESULTS

Comparison of modelled and actual yield of individual forages used in the rotation

Actual historical yield data of individual forages (used in the rotation simulations) was predicted relatively moderately ($R^2 = 0.58$) by the simulated yield of the respective individual forages (Figure 1; Table 4).

Grazeable forage options and simulated yields from different rotation options

Maize and forage rape-ryegrass rotations provided simulated yields of a total of 28.2, 27.8, 26.0, and 25.3 t DM/ha grazeable forages respectively for 10 October, 20 October, 20 November and 20 December sowing treatments (Table 5). There was a consistent trend of maize yield declining as the sowing date progressed from 10 October to 20 December. As sowing dates for forage rape over-sown with ryegrass progressed the simulated yield of forage rape decreased from 10.0 to 8.2 t DM/ha but this coincided with ryegrass yields increasing from 5.8 to 6.5 t DM/ha. The increased ryegrass yields were insufficient to counteract the decrease in forage rape yields resulting in overall simulated yields of late sowing of forage rape-ryegrass combinations decreasing from 15.8 t DM/ha to 14.7 t DM/ha. As a result of decrease of yields of both maize and forage rape-ryegrass, total simulated grazeable forage yields from this rotation also decreased due to late sowing (Table 5).

Total grazeable simulated yields from soybean-based rotations were 22.9, 22.9, 22.4, and 21.5 t DM/ha respectively for 15 October, 15 November, 30 November and 15 December sowing (Table 5). The pattern of decrease in soybean (9.5 to 7.6 t DM/ha) and forage rape (8.3 to 7.9 t DM/ha), and increase in ryegrass (5.1 to 6.0 t DM/ha) in soybean-based rotations due to late sowing was similar to the maize-based rotations. However, simulated yields of both forage rape and ryegrass in soybean-based rotations were lower compared to those obtained from maize-based rotations.

As a consequence of the limited number of simulated grazings of sorghum (particularly in late sowings) combined with the late sowing of forage rape-ryegrass, total simulated grazeable forage yields were 19.3, 19.1, 19.1, and

Table 5. Simulated forage yields (t DM/ha) in rotations of maize, soybean and sorghum sown in summer followed by forage rape (over-sown or intercropped) with ryegrass

| Rotations | Simulations $^1$ | Simulated forage yields (t DM/ha) | Total simulated forages (t DM/ha/yr) (SD) |
|-----------|-----------------|----------------------------------|-------------------------------------------|
|           |                 | M/S/Sg                           | Forage rape-ryegrass intercrop            |                                           |
|           |                 |                                  | Forage rape | Ryegrass | Total   |                                           |
| Maize     | M1              | 12.4                             | 10.0       | 5.8      | 15.8    | 28.2 (1.7)                                |
|           | M2              | 12.1                             | 9.5        | 6.2      | 15.7    | 27.8 (1.6)                                |
|           | M3              | 11.3                             | 8.5        | 6.2      | 14.7    | 26.0 (1.7)                                |
|           | M4              | 10.6                             | 8.2        | 6.5      | 14.7    | 25.3 (1.5)                                |
| Soybean   | S1              | 9.5                              | 8.3        | 5.1      | 13.4    | 22.9 (0.9)                                |
|           | S2              | 9.4                              | 8.0        | 5.5      | 13.5    | 22.9 (1.0)                                |
|           | S3              | 9.0                              | 7.9        | 5.5      | 13.4    | 22.4 (0.9)                                |
|           | S4              | 7.6                              | 7.9        | 6.0      | 13.9    | 21.5 (1.1)                                |
| Sorghum   | Sg1             | 10.2                             | 4.6        | 4.5      | 9.1     | 19.3 (1.3)                                |
|           | Sg2             | 9.7                              | 4.6        | 4.8      | 9.4     | 19.1 (0.9)                                |
|           | Sg3             | 9.1                              | 5.0        | 5.1      | 10.1    | 19.2 (0.9)                                |
|           | Sg4             | 6.8                              | 4.7        | 5.4      | 10.1    | 16.9 (1.7)                                |

DM, dry matter; SD, standard deviation.

$^1$ M, S, and Sg represents maize, soybean and sorghum respectively each followed by an intercrop of forage rape-ryegrass rotation. Sowing dates and all other agronomic principles can be seen in Table 2.
Table 6. Simulated monthly mean daily growth rate (kg DM/ha/d) of forages in maize and forage rape oversown with ryegrass at different sowing dates (M1).

|       | M1         | M2         | M3         | M4         |
|-------|------------|------------|------------|------------|
|       | Maize      | Forage rape| Rye grass  | Maize      | Forage rape| Rye grass  | Maize      | Forage rape| Rye grass  |
| Jan   | 56.6       | 135.2      | 265.0      | 53.6       | 0          | 0          |
| Feb   | 0          | 0          | 0          | 0          | 0          | 0          |
| Mar   | 0          | 0          | 0          | 0          | 0          | 0          |
| Apr   | 0          | 0          | 0          | 0          | 0          | 0          |
| May   | 0          | 0          | 0          | 0          | 0          | 0          |
| Jun   | 0          | 0          | 0          | 0          | 0          | 0          |
| Jul   | 0          | 0          | 0          | 0          | 0          | 0          |
| Aug   | 0          | 0          | 0          | 0          | 0          | 0          |
| Sep   | 0          | 0          | 0          | 0          | 0          | 0          |
| Oct   | 0          | 0          | 0          | 0          | 0          | 0          |
| Nov   | 0          | 0          | 0          | 0          | 0          | 0          |
| Dec   | 0          | 0          | 0          | 0          | 0          | 0          |
| Grand total | 34.2     | 27.3       | 15.7       | 33.4       | 26.0       | 16.7       |

1 M represents sowing dates of forages. Sowing dates and all other agronomic principles can be seen in Table 2.

16.9 t DM/ha respectively for 15 October, 15 November, 30 November and 15 December sowing of sorghum in sorghum-based rotations (Table 5). Late sowing reduced simulated grazeable sorghum yields substantially.

Standard deviations (based on 111 years) of maize, soybean and sorghum based rotations ranged from 1.5 to 1.7, 0.9 to 1.1, and 0.9 to 1.7 t DM/ha, respectively (Table 5), which indicates that under non-limiting inputs yield differences between years would be minimal from these rotations.

Growth rates of forages in different forage options, forage supply and critical periods

Simulated monthly and annual (average of all months) mean daily growth rates of different forages in different rotations are presented in Table 6 (maize rotations), Table 7 (soybean rotations) and Table 8 (sorghum rotations). Growth rates of forages in maize-based rotations were higher compared to forages in other rotations.

There were two common features of grazeable forage supplies in all rotations. Firstly, all rotations (except Sg4) were able to supply grazeable forages to a varied degree for approximately eight months of the year. Secondly, the rest of the four months of the year were critical periods when grazeable forage supplies were not available. These critical periods were approximately two months after sowing of summer forage crops followed by a period of two months after sowing of forage rape in the rotation.

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Table 7. Simulated monthly mean daily growth rate (kg DM/ha/d) of forages in soybean and forage rape oversown with ryegrass at different sowing dates (S1)

|       | S1        | S2        | S3        | S4        |
|-------|-----------|-----------|-----------|-----------|
|       | Soy-bean  | Forage rape| Rye grass | Soy-bean  | Forage rape| Rye grass | Soy-bean  | Forage rape| Rye grass |
| Jan   | 102.3     | 70.9      | 123.7     | 101.4     | 0          | 0          |
| Feb   | 50.6      | 115.9     | 53.8      | 57.2      | 0          | 0          |
| Mar   | 0         | 30.5      | 90.2      | 89.5      | 0          | 0          |
| Apr   | 0         | 27.2      | 12.5      | 7.4       | 0          | 0          |
| May   | 0         | 99.3      | 60.7      | 49.8      | 0          | 0          |
| Jun   | 0         | 20.3      | 72.4      | 79.8      | 6.8        |
| Jul   | 0         | 5.4       | 4.3       | 12.7      | 18.5       |
| Aug   | 0         | 53.2      | 12.0      | 9.7       | 44.8       |
| Sep   | 0         | 52.8      | 80.9      | 79.4      | 24.3       |
| Oct   | 0.9       | 3.1       | 17.6      | 21.9      | 56.1       |
| Nov   | 53.3      | 1.4       | 0         | 0         | 45.5       |
| Dec   | 102.8     | 8.8       | 27.4      | 2.3       | 0          |
| Grand average | 25.4     | 22.7      | 24.2      | 20.6      | 21.6       |

1 S represents sowing dates of forages. Sowing dates and all other agronomic principles can be seen in Table 2.
simulated yields and irrigation requirements

There were 56 neutral (normal), 29 La-Nina and 26 El-Nino years in 111 years and irrigation and temperature related risks associated with El-Nino years was assessed. Average daily maximum temperature (23.7°C) and radiation (17.2 MJ/m²) was slightly higher in El-Nino years compared to neutral years (23.2 and 17.0 respectively), but radiation was lower in La-Nina (16.6 MJ/m²) compared to neutral years (Table 9). Under non-limiting irrigation water and N fertilizer, total DM yield for a particular simulation was similar between neutral and El-Nino or La-Nina years (Table 10). Irrigation water requirements could increase by up to 18%, 16%, and 17% respectively in those rotations in El-Niño years compared to neutral years (Table 10). On the other hand, irrigation requirement could increase by up to 25%, 23%, and 32% in maize, soybean and sorghum based rotations in El-Niño years compared to La-Nina years. However, irrigation requirement could decrease by up to 8%, 7%, and 13% in maize, soybean and sorghum based rotations in La-Niña years compared to neutral years (Table 10).

**DISCUSSION**

Model comparison (evaluation) with individual forages

| ENSO events | No. of years | Rainfall (mm) | Radiation (MJ/m²) | Max temp. (°C) | Min temp. (°C) |
|-------------|--------------|---------------|-------------------|----------------|----------------|
| Neutral     | 56           | 672.0         | 17.2              | 23.7           | 10.7           |
| La-Nina     | 29           | 813.1         | 16.6              | 23.2           | 10.7           |
| El-Nino     | 26           | 729.2         | 17.0              | 23.2           | 10.8           |
| Average/total | 111          | 738.1         | 16.9              | 23.4           | 10.7           |

1 ENSO Southern Oscillation.
evidences suggest that the dynamic simulation of the APSIM model successfully represented key agronomic, physiological and production system behavior that have occurred in the experimental paddocks or fields. Therefore, it is expected that the simulated forage yields from similar type of forage rotations as those carried out in the present study might be realistic.

In addition, we have also demonstrated that APSIM was able to validate ($R^2 = 0.81$) actual yield of total CFR grown under a range of N (from 0 to 523 kg/ha) and water (0 to 14 ML water/ha) (Islam and Garcia, 2010). This evidence further suggests that the APSIM model is underpinned by sound scientific-based principles and biologically explainable for forage crop rotations and may be used to explore various other forage rotations as in the present study for the benefit of the livestock industry.

Finally, our measured actual yields of individual forages (used in rotations in this study) from various field trials and then simulation of same forages with the same agronomic principles (e.g. sowing date) and inputs (e.g. N and water

| Simulations | Years | M/S/Sg | Forage | Ryegrass | Total (t DM/ha) | Irrigation (mm) | Total water (mm) |
|-------------|-------|--------|--------|----------|----------------|----------------|----------------|
| M1          | El-Niño | 12.4   | 10.6   | 5.9      | 28.9           | 639.6          | 1,312          |
|             | La-nina | 11.7   | 10.0   | 5.7      | 27.4           | 510.7          | 1,324          |
|             | Neutral | 12.2   | 10.0   | 5.8      | 28.0           | 545.5          | 1,275          |
| M2          | El-Niño | 12.5   | 9.5    | 6.2      | 28.2           | 632.8          | 1,305          |
|             | La-nina | 11.7   | 9.5    | 6.1      | 27.3           | 510.7          | 1,324          |
|             | Neutral | 12.2   | 9.5    | 6.1      | 27.8           | 552.4          | 1,282          |
| M3          | El-Niño | 11.0   | 8.6    | 6.3      | 25.9           | 673.8          | 1,346          |
|             | La-nina | 10.8   | 8.4    | 6.1      | 25.3           | 554.5          | 1,368          |
|             | Neutral | 11.3   | 8.5    | 6.2      | 26.0           | 579.1          | 1,308          |
| M4          | El-Niño | 10.7   | 8.1    | 6.6      | 25.4           | 671.5          | 1,344          |
|             | La-nina | 10.6   | 8.2    | 6.5      | 25.3           | 540.8          | 1,354          |
|             | Neutral | 10.6   | 8.2    | 6.5      | 25.3           | 567.2          | 1,296          |
| S1          | El-Niño | 9.6    | 8.3    | 5.2      | 23.1           | 698.5          | 1,371          |
|             | La-nina | 9.5    | 8.5    | 5.1      | 23.1           | 567.5          | 1,381          |
|             | Neutral | 9.3    | 8.4    | 5.1      | 22.8           | 609.7          | 1,339          |
| S2          | El-Niño | 9.4    | 7.8    | 6.0      | 23.2           | 731.5          | 1,404          |
|             | La-nina | 9.4    | 8.2    | 5.3      | 22.9           | 589.3          | 1,402          |
|             | Neutral | 9.5    | 8.0    | 5.4      | 22.9           | 633.1          | 1,362          |
| S3          | El-Niño | 9.2    | 8.0    | 5.7      | 22.9           | 722.3          | 1,394          |
|             | La-nina | 8.9    | 7.8    | 5.3      | 22.0           | 588.4          | 1,402          |
|             | Neutral | 9.0    | 7.9    | 5.6      | 22.5           | 626.2          | 1,352          |
| S4          | El-Niño | 7.7    | 7.8    | 6.1      | 21.6           | 683.9          | 1,356          |
|             | La-nina | 7.3    | 7.8    | 6.0      | 21.1           | 553.0          | 1,366          |
|             | Neutral | 7.7    | 8.0    | 6.0      | 21.7           | 595.8          | 1,325          |
| So1         | El-Niño | 10.8   | 4.5    | 4.4      | 19.7           | 525.4          | 1,197          |
|             | La-nina | 9.8    | 4.7    | 4.4      | 18.9           | 400.1          | 1,213          |
|             | Neutral | 9.9    | 4.6    | 4.4      | 18.9           | 451.6          | 1,181          |
| So2         | El-Niño | 9.9    | 4.6    | 4.8      | 19.3           | 493.7          | 1,166          |
|             | La-nina | 9.6    | 4.6    | 4.8      | 19.0           | 384.9          | 1,198          |
|             | Neutral | 9.6    | 4.7    | 4.8      | 19.1           | 434.6          | 1,164          |
| So3         | El-Niño | 9.2    | 5.1    | 5.2      | 19.5           | 484.8          | 1,157          |
|             | La-nina | 9.0    | 4.9    | 5.1      | 19.0           | 367.5          | 1,181          |
|             | Neutral | 9.0    | 4.9    | 5.1      | 19.0           | 422.2          | 1,151          |
| So4         | El-Niño | 7.0    | 4.8    | 5.5      | 17.3           | 433.3          | 1,105          |
|             | La-nina | 6.9    | 4.6    | 5.4      | 16.9           | 326.8          | 1,140          |
|             | Neutral | 6.4    | 4.6    | 5.4      | 16.4           | 369.8          | 1,099          |

1 M, S, and Sg represents maize, soybean and sorghum respectively each followed by an intercrop of forage rape-ryegrass rotation. Sowing dates and all other agronomic principles can be seen in Table 2.
rates and timing) used in the field trials revealed that simulated yields were reasonably well correlated to actual forage yields ($R^2 = 0.58$). Therefore, although the simulation rotation scenarios used in this study were not validated using field experiments per se, closely matched simulated and actual yields of individual forages used in the rotations in this study indicate that simulated yields obtained from these forage rotations might be realistic. Nonetheless, one limitation of the validation is that none of the simulations including intercropping of forage rape and ryegrass used in this study was validated using data generated from field studies.

### Grazeable forages for automatic milking system herds and critical periods of supply

The main objective of this study was to identify a suitable forage option that can provide high yield as well as supply grazeable forages for AMS herds throughout the year. The simulated yields indicate that maize-based rotations have the potential to provide between 25.3 and 28.2 t DM/ha followed by soybean-based rotations (between 21.5 and 22.9 t DM/ha). Simulated sorghum based rotations supplied lower total forage yields; however, in practice more forage supply may be achieved which will be discussed later. The results presented here indicate that maize-based rotations may have the potential to supply 49% to 66% higher yields of grazeable forages for AMS compared to traditional well managed pastures (17 t DM/ha; Garcia et al., 2007b). This in turn may reduce the grazing area at a similar rate required to grow pastures for AMS herds. Therefore, maize-based rotations of this simulation study may have considerable potential to reduce average walking distances of a large AMS herd and consequently may decrease milking interval and increase milk yield. Similarly, there is a good prospect of soybean-based rotations to increase cow-traffic for a large AMS herds as grazeable forage yields from these rotations increased by 27% to 35% compared to pastures.

In order to maximise grazing (both grazed yield and grazing days) from these rotations, some principles of grazing may need to follow. For example, grazing of maize can commence when the crop reaches 5 t DM/ha (or more), which is generally between 45 and 55 days after sowing. The window of opportunity for grazing of maize may last for up to 40 days after which the crop will likely be too mature to graze (crop ends at Zadoks growth stage 8). Similarly, the first grazing of soybean should be expected to commence approximately 55 days after sowing and all areas of the crop should be grazed before initiation of flowering to ensure full potential is harnessed with high re-growth. The subsequent re-growth of soybean should be expected to be grazed after a similar interval. For sorghum, first grazing may be started approximately 50 to 60 days after sowing and then 30 to 40 days after each grazing.

Grazing of forage rape-ryegrass will by default be synchronized as the two forages are intercropped. Some yield may be compromised if grazing must occur at less than ideal maturity for either the forage rape or the ryegrass. Therefore, planning the grazing schedule would be expected to play a significant role in maximization of yield and DM intake from these forages.

Overall, our simulations showed that most rotations used in this study may be able to supply grazeable forages for AMS herds for at least 8 months of the year. The most critical periods when forage supply may not be available were approximately 2 months immediately after sowing of summer forages such as maize, soybean or sorghum and similarly 2 months after sowing of forage rape. Unfortunately these two critical periods have the potential to coincide with periods of reduced pasture supply on the wider farm area particularly for some of the sowing date simulations. One possible solution could be to stagger the sowing date of the forage crops to extend the viable grazing periods thereby increasing the potential to minimise the critical periods in discussion. Another approach could be growing forages that are grazeable during the critical 4 months. Maize or other forages may also be grown and conserved (preferably in more distant paddocks) and may be offered during those critical times. In situations where these approaches are not valid, purchased feed may be necessary to fill the feed gap during these critical periods.

### Growth of forages in different forage option rotations

Our simulated results suggest that the decision on which of the crops should be grown in the rotation in summer to supply forages for AMS herd might influence the total output. Simulation results showed that high forage yield may be achieved from maize-based compared to other rotations. This high potential yield of maize-based rotations was due to a higher yield of both summer and autumn-winter crops compared to soybean and sorghum.

The physiological basis for this high yield of maize is well established. Dry matter production is a function of light interception and the efficiency of use of absorbed radiation (Andrade et al., 1993). The erectophile leaves of maize compared to horizontal leaves of soybean allow a more uniform distribution of the incoming radiation (Awal et al., 2006). This is an advantage for canopy photosynthesis and radiation use efficiency of maize at a high leaf area index. Radiation use efficiency of maize (2.77 g/MJ) is higher than soybean (1.74 g/MJ) (Andrade, 1995). As a result, the photosynthetic system of maize was more efficient than soybean, which enables maize to develop more biomass.

Simulated yields of forage rape alone (when over-sown or intercropped with ryegrass) in all forage options were
Impact of El-Nino Southern Oscillation events on simulated yields and irrigation requirements

These results indicate that irrigation requirements could increase up to 18% in El-Nino, but decrease up to 13% in La-Nina compared to neutral years. This increase in irrigation in El-Nino years resulted in little or no gain in yield in most of the simulated scenarios, which is in agreement with the results of Chauhan (2010). High and low irrigation requirements in El-Nino and La-Nina years, respectively might be attributable to daily average radiation interception and maximum temperature which were higher in El-Nino and lower in La-Nina years compared to neutral years for only a small gain in yield in El-Nino years. This result also agrees with Chauhan (2010), who reported higher solar radiation and maximum temperature in El-Nino years despite similar minimum temperature across ENSO events.

Overall, although the impact of ENSO events were minimal on simulated yields, their impact on irrigation water requirements was significant. As both El-Nino and La-Nina occur on average one in every four year (based on data of 111 years from 1900 to 2010), forecasting tools can potentially be valuable tool in determining water requirement for a particular rotation and year in response to differences in rainfall, so that one can plan optimal area required to supply feed for AMS herds under irrigation for a given amount of irrigation water allocation in El-Nino and La-Nina years.

CONCLUSION

The results of our study indicate that the APSIM model has the potential to screen grazeable forage options for AMS herds. APSIM simulations also showed that there is a considerable potential to increase grazeable forages (16.9 to 28.2 t DM/ha) for AMS herds compared to current levels of pasture yield (17 t DM/ha) using strategic forage rotations. The results also showed that these simulations may indicate periods of reduced forage availability including critical periods which would require management. One major implication of this study is that APSIM models may assist in devising preferred forage options in order to maximise grazeable forage yield for AMS herds. It may create an opportunity to grow more forage in small areas around the AMS which in turn will minimise walking distance and milking interval and thus increase milk production. Ultimately this should also help to reduce purchased feed and cost of production. Yield variability of the simulated forages in the rotations were minimal between years under non-limiting inputs, but irrigation water requirements were higher in El-Nino years compared to La-Nina and neutral years. Overall, APSIM can be used as a valuable tool to
assist in devising preferred grazable forage options in a production system such as for AMS herds. It may also provide decision support by identifying critical periods when alternatives are needed and risk assessment during climatic uncertainty. Further work should be conducted regarding system fitness of the forage crops to the wider farm and herd. This would ensure that a more integral understanding of the full system could be developed including balancing the diet and need for supplementary feeds.

ACKNOWLEDGMENTS

The authors thank the Dairy Research Foundation for its support of the Dairy Science Group and the investors of the FutureDairy project (Dairy Australia, NSW Department of Primary Industries, The University of Sydney, and DeLaval). The authors also acknowledge Dr K. Pemberton, University of Tasmania for his suggestion in constructing sorghum-based simulations.

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