COMPREHENSIVE MEASUREMENT OF ALL ENERGY BUDGET COMPONENTS TO IMPROVE CLOSURE

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In this study, comprehensive measurements for all energy budget components were measured to examine closure. This included the use of soil heat pulse probes for measuring soil heat flux and soil heat storage, which captured greater soil heterogeneity. When all storage terms were accounted for, a linear regression was applied to the energy budget data and the slope was found to be 0.99 with an intercept of 2.46 ($R^2 = 0.93$). It was also found that the total daily latent heat flux had an influence on the closure accounting for ~40% (P-value < 0.05) of the variability. The total sensible heat flux did not have a similar relationship ($R^2 < 0.1$, P-value > 0.05). Least squares regression and inverse matrix analysis was applied to sets of 24-hour half-hour eddy covariance data to identify areas of error; however, results were inconclusive.
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TABLE OF CONTENTS

1 INTRODUCTION..................................................................................................................1
  1.1 Literature Review...........................................................................................................1
    1.1.1 Sources of Error.......................................................................................................2
      1.1.1.1 Net Radiation.................................................................................................2
      1.1.1.2 Storage Terms...............................................................................................3
      1.1.1.3 Mismatch in Footprint....................................................................................8
      1.1.1.4 Adveotive Flux Divergence..............................................................................9
      1.1.1.5 Large-Scale Turbulent Structures.................................................................10
      1.1.1.6 Frequency Response Corrections.................................................................12
    1.1.2 Forcing Closure....................................................................................................14
    1.1.3 Summary.............................................................................................................16
  1.2 Objectives....................................................................................................................18
  1.3 Thesis Organization....................................................................................................18

2 EDDY COVARIANCE ENERGY BUDGET CLOSURE..................................................19
  2.1 Introduction................................................................................................................19
  2.2 Methodology.............................................................................................................22
    2.2.1 Field Site...........................................................................................................22
    2.2.2 Theory...............................................................................................................23
    2.2.3 Field Setup and Instrumentation.........................................................................25
    2.2.4 Eddy Covariance Data Processing........................................................................28
    2.2.5 Data Analysis....................................................................................................28
  2.3 Results.......................................................................................................................29
    2.3.1 Component Partitioning......................................................................................29
    2.3.2 Energy Budget Closure......................................................................................32
2.3.3 Daily Closure ................................................................. 34
2.3.4 Energy Budget Closure and Turbulent Fluxes .................. 36
2.3.5 Soil Heat Flux ..................................................................... 39
2.3.6 Air Heat Storage ............................................................... 42
2.3.7 Least Squares Regression and Inverse Matrix Analysis ....... 43
2.4 Discussion ............................................................................ 45
2.4.1 Component Partitioning ...................................................... 45
2.4.2 Energy Budget Closure ...................................................... 47
2.4.3 Daily Closure ..................................................................... 48
2.4.4 Energy Budget Closure and Turbulent Fluxes .................. 49
2.4.5 Soil Heat Flux ..................................................................... 51
2.4.6 Air Heat Storage ............................................................... 52
2.4.7 Least Squares Regression and Inverse Matrix Analysis ....... 52
2.5 Conclusion ............................................................................ 53

3 CONCLUSION ........................................................................ 54
3.1 Introduction .......................................................................... 54
3.2 Literature Review ............................................................... 54
3.3 First Objective ..................................................................... 55
3.4 Second Objective ............................................................... 56

BIBLIOGRAPHY ....................................................................... 57
LIST OF TABLES

2.1 Results from least squares regression and matrix analysis for composite
daily data for DOY 198-243, July, and August........................................ 44
2.2 Results from least squares regression and inverse matrix analysis for
multiple days in July and August............................................................ 45

LIST OF FIGURES

1.1 Scatterplot of $H + LE$ and $H + LE + S$, respectively, versus net radiation.
Source: Lindroth et al. (2010)............................................................... 6
2.1 Composite half-hour diurnal plot of net radiation ($R_n$), sensible heat flux
($H$), latent heat flux ($LE$), soil heat flux ($G$), soil heat storage ($\Delta S_s$), air heat
storage ($\Delta S_a$) and crop heat storage ($\Delta S_c$) for DOY 198 – 243. Error bars
are the standard error of the mean......................................................... 31
2.2 Half-hour diurnal plots for net radiation ($R_n$), sensible ($H$), latent ($LE$), and
soil ($G$) heat flux, soil heat storage ($\Delta S_s$), air heat storage ($\Delta S_a$) and crop
heat storage ($\Delta S_c$) for August (a) 3rd, (b) 5th, (c) 7th, and (d)
23rd........................................................................................................ 32
2.3 (a) & (b) Scatterplots of turbulent fluxes ($H + LE$) versus available energy
($Rn – G$ with and without storage terms, respectively) for half-hourly-
averaged measurements at Elora Research Station. Panels (c) & (d) show
the corresponding composite diurnal plots for DOY 198 to 243 where error
bars are the standard error of the mean................................................. 34
2.4 Values for energy budget closure obtained through simple linear regression for DOY 198 to 243 where error bars are the standard error of the mean.

2.5 Half-hour diurnal plots of net radiation ($R_n$), sensible ($H$), latent ($LE$), and soil ($G$) heat flux, soil heat storage ($\Delta S_s$), air heat storage ($\Delta S_a$) and crop heat storage ($\Delta S_c$) for July (a) 29th, (b) 30th, (c) 31st, and (d) August 27th.

2.6 Scatterplot of daily closure values obtained through simple linear regression versus the latent heat flux ($LE$) for DOY 198-243.

2.7 Scatterplot of latent heat flux ($LE$) versus sensible heat flux ($H$) for DOY 198-243.

2.8 Scatterplot of residuals from daily closure and latent heat flux ($LE$) regression versus HPP soil heat flux ($G$) variance.

2.9 Scatterplot of mean $G$ measured by the HPP versus mean $G$ measured by HFP for data collected from the Elora Research Station.

2.10 (a) Scatterplot of turbulent fluxes ($H + LE$) versus available energy ($R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$, where $G$ is from HFP), (b) scatterplot of turbulent fluxes ($H + LE$) versus available energy ($R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$, where $G$ is from HFP) and (c) & (d) are the corresponding diurnal plot where error bars are the standard error of the mean.

2.11 Composite diurnal plots with partitioned energy budget terms for DOY 198-243 where (a) is $G$ measured using the HPP and (b) has $G$ measured using the HFP. Error bars are the standard error of the mean.

2.12 Scatterplot of air storage calculated from the air profile versus air storage calculated from the sonic temperature.
CHAPTER 1: INTRODUCTION

1.1 LITERATURE REVIEW

Energy budget closure is the balance between the sum of sensible \((H)\) and latent \((LE)\) heat fluxes, and the available energy (i.e. net radiation \((R_n)\) minus the soil heat flux \((G)\) and the storage terms \((\Delta S)\)).

\[
H + LE = R_n - G - \Delta S
\] (1.1)

At most flux research sites energy budget closure is not reached and an imbalance remains (Aubinet et al., 2000; Wilson et al., 2002). Many published studies give results from eddy covariance energy budget closure. The degree of closure these studies achieve can vary greatly from ~10% to greater than 30% (Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002). Historically, this imbalance has been attributed to the underestimation of turbulent fluxes.

The imbalance in the energy budget becomes an issue when turbulent fluxes measured by the eddy covariance technique are used to calibrate and/or validate models; such is the case with soil-vegetation-atmosphere transfer (SVAT) models and land surface models (LSMs) (Foken et al., 2008; Williams et al., 2009). In addition, the imbalance raises the concern that if the sensible and latent heat fluxes are systematically underestimated then perhaps the CO\(_2\) fluxes measured by eddy covariance are incorrect as well (Baldocchi, 2008).
The cause of this imbalance has been widely debated in the literature. This review will focus on the main causes and theories behind why this imbalance occurs and the methods that have been proposed to account for it. The sources of errors that this review will focus on will include instrumentation issues, such as issues with the measurements for net radiation (Cobos and Baker, 2003; Kohsiek et al., 2007; Leuning et al., 2012), storage components (Emmel et al., 2013; Leuning et al., 2012; Lindroth et al., 2010), or a mismatch in instrument footprint (Culf et al., 2004; Foken, 2008; Oncley et al., 2007), the presence of turbulent structures (Finnigan et al., 2003; Foken, 2008; Harman and Finnigan, 2010; Katul et al., 2006), and errors with frequency response corrections (Leuning et al., 2012). In addition, this review will also cover various methods for forcing closure (Twine et al., 2000; Wohlfahrt et al., 2009).

1.1.1 Sources of Error

1.1.1.1 Net Radiation

Net radiation is the equilibrium between the incoming and outgoing energy at the earth’s surface. In the energy budget equation it is the measure of the available energy to the system. For the net radiation to explain the energy imbalance there would need to be a systematic overestimation of available energy. Depending on the make and model of the net radiometer used there can be inconsistencies (Field et al., 1992; Kohsiek et al., 2007; Kustas et al., 1998). In a side-by-side comparison of seven different net radiometers designed by five manufacturers, Field et al. (1992) found a daytime difference of 5-7% for instruments of the same manufacturer and a 10-15% difference between different manufacturers. In more recent years, in the EBEX-2000 experiment, several radiometers
of various manufacturers were compared (Kohsiek et al., 2007). It was found that the daytime maximum error of net radiation was 25 W m\(^{-2}\) (5\%) and the nighttime maximum error was 10 W m\(^{-2}\). These differences in net radiometers would produce random errors, which could lead to either an over- or underestimation. Thus, differences in net radiometers are not enough to account for the systematic difference between available energy and turbulent fluxes (Leuning et al., 2012).

Further net radiation errors occur when working over complex, sloping terrain, which results in the net radiation being out of phase with other measurements (Leuning et al., 2012; Serrano-Ortiz et al., 2016). In such cases net radiation measurements should be taken either parallel to the slope (Matzinger et al., 2003; Serrano-Ortiz et al., 2016), or the horizontal net radiation should be corrected (Hammerle et al., 2007; Hiller et al., 2008; Wohlfahrt et al., 2016). Methods for correcting the horizontal net radiation include using the average inclination and aspect of the slope (Hammerle et al., 2007; Hiller et al., 2008) or a more complicated approach, which takes into account the spatial variability of the inclination and aspect of the underlying surface and weights it with the flux footprint contribution (Wohlfahrt et al., 2016). Both these methods result in similar net radiation values (Wohlfahrt et al., 2016).

1.1.1.2 Storage Terms

The soil heat flux is the rate of energy transfer downwards through the soil. It is a necessary component to the energy balance equation, as its neglect would lead to a systematic overestimation of available energy. It is common practice for soil heat flux measurements to be taken using one or two heat flux plates at several centimeter depths
in order to avoid the layer near the surface where energy is used to evaporate water (Heitman, 2010). However, it has been demonstrated that in arid desert regions, where there is very little latent heat storage in soils, heat flux plates can be buried just a few millimeters below the surface (Heusinkveld et al., 2004). In Heusinkveld et al. (2004)’s study, this resulted in greater accuracy in the heat flux measurements.

In most other cases, when soil heat flux is not measured at the surface, a term for soil heat storage above the point of soil heat flux measurement should be included in the energy balance equation (Leuning et al., 2012; Ochsner et al., 2007; Oliphant et al., 2004). The soil heat storage can account for a significant amount of energy with the top 2 cm storing up to 40 W m$^{-2}$ (Kukharets and Tsvang, 1999). Therefore, neglecting to include soil heat storage in the energy budget equation would be a systematic error that causes an overestimation of the available energy.

Common practice for estimating the soil heat storage term uses measurements for soil temperature and soil volumetric heat capacity. In Ochsner et al. (2007), three methods for determining soil volumetric heat capacity were compared: soil sampling to determine mass water content, soil moisture sensors (ThetaProbe), and heat pulse probes (HPP). They found that the heat pulse probe method was the most accurate at measuring the temporal variability of soil volumetric heat capacity; however, all three methods provided similar values (within 6% agreement). Of the three methods, only the heat pulse probes directly measure the soil heat capacity and the soil temperature. Oschner et al. (2007) concluded that these traits along with their small size make the heat pulse probe method well suited for measuring heat storage near the soil surface.
Campbell et al. (1991) first introduced the heat pulse probe method with a design consisting of one heater needle and one thermistor needle spaced 6 mm apart. The probes could be used to calculate the thermal properties of soil based on heat transfer theory (Campbell et al., 1991). Later, Bristow et al. (1994) added a second thermistor needle to the probe so that all three needles were in parallel with the heater needle in the center. The addition of the second thermistor needle improved Campbell et al. (1991)’s design by creating more measurement repetitions.

The significance of soil heat flux and storage can vary depending on vegetation type. For example, a forest with a dense canopy would have far less soil heat flux and soil heat storage than that of an agricultural field or sparse desert because less radiation reaches the surface. Instead, under forest conditions, an appreciable amount of energy storage can be found in the biomass and air layer between the surface and the point of turbulent flux measurement.

In Lindroth et al. (2010), biomass energy storage in the trees was the dominant heat energy storage term, reaching a maximum daytime flux of 22 W m\(^{-2}\). Comparatively, both the soil heat flux and air heat storage reached similar daytime maxima of approximately 15 W m\(^{-2}\). Figure 1.1 shows the plotted results for half-hour averages of the sensible and latent heat fluxes with and without the storage term versus the net radiation. When the storage terms are neglected, the slope of the line is 0.857 with an intercept of 9.89. The inclusion of the storage term brings the slope of the line closer to unity at 0.975 with an intercept of -2.28. There is also a decrease in the amount of scatter with \(R^2\) increasing from 0.918 to 0.947. This shows that in forest sites the biomass and air
heat storage terms are important components in the energy budget equation and should be included to avoid systematic error (Leuning et al., 2012; Lindroth et al., 2010).

For measuring the heat storage in biomass Lindroth et al. (2010) used thermocouples inserted into the trunks of various trees and the heat capacities for wood and bark. The Meesters and Vugts (1996) methodology for calculating heat storage in biomass was then applied to the data. The method used for measuring biomass heat storage will vary depending on the vegetation type. For agricultural fields, Meyers and Hollinger (2004) determined biomass energy storage using infrared thermometry and biomass

![Figure 1.1 Scatterplot of H + LE and H + LE + S, respectively, versus net radiation. Source: Lindroth et al. (2010).](image)
measurements. When they included this measurement along with measurements for energy storage in the air and soil they found that closure calculated through linear regression improved by 10% for corn and by 7% for soybeans, with 5% more variability explained. Therefore, biomass storage, which is often neglected in the energy budget equation, is an important component over both dense forest canopies and agricultural fields.

During photosynthesis, plants account for a portion of the available energy in biochemical energy storage. Biochemical energy storage is often neglected in the energy budget equation. Although it only accounts for a small portion of energy over agricultural fields (Leuning et al. 2012), it can be one of the largest storage components within forest canopies (Emmel et al., 2013). In Emmel et al. (2013), the energy stored during photosynthesis was calculated based on the CO\(_2\) flux measured by eddy covariance at 7 heights within the canopy using the following equation:

\[
\Delta Q_{S,C} = \left( \frac{\partial F_C}{\partial z} + (1 - \theta_{tree}) \frac{\partial \rho_C}{\partial t} \right) \phi_a, \tag{1.2}
\]

where \(\Delta Q_{S,C}\) is the energy stored, \(F_C\) is the CO\(_2\) flux (kg s\(^{-1}\) m\(^{-2}\)), \(\theta_{tree}\) is the volumetric fraction occupied by trees (m\(^3\) m\(^{-3}\)), \(\rho_C\) is CO\(_2\) density in air (kg m\(^{-3}\)), \(\phi_a\) is the heat of CO\(_2\) assimilation (1.15 x 10\(^7\) J kg\(^{-1}\), Oke (1987)), \(\frac{\partial F_C}{\partial z}\) is the vertical CO\(_2\) flux divergence (kg m\(^{-3}\) s\(^{-1}\)), and \(\frac{\partial \rho_C}{\partial t}\) is the concentration change of CO\(_2\) over time (kg m\(^{-3}\) s\(^{-1}\)). To account for soil respiration, a constant of 1.2 \(\mu\)mol m\(^{-2}\) s\(^{-2}\) was used in the lower boundary of the canopy. During the study period, the soil moisture remained low allowing for a relatively constant soil respiration. It was found that in the lower canopy, the dominant storage
terms were the biomass heat storage and biochemical heat storage, while in the upper canopy air storage was dominant.

Biochemical energy storage has been calculated for agricultural fields (Jacobs et al., 2008; Meyers and Hollinger, 2004); however, soil respiration was either neglected or hard to account for. Although the methods used have been debated, Jacobs et al. (2008) and Meyers and Hollinger (2004), found that including biochemical energy storage in the energy budget equation for agricultural fields helped to improve closure. Here biochemical energy storage was estimated from the approximation that \( \approx 422 \text{ kJ} \) of energy per mole of \( \text{CO}_2 \) is fixed by the photosynthesis process (Nobel, 1974); therefore, a canopy assimilation rate of \( 1 \text{ mg} \text{ CO}_2 \text{ m}^{-2} \text{ s}^{-1} \) is equal to \( 11 \text{ W m}^{-2} \) (Jacobs et al., 2008; Meyers and Hollinger, 2004; Nobel, 1974).

1.1.1.3 Mismatch in Footprint

Eddy covariance measurements of latent and sensible heat fluxes take averages over the fetch rather than single point measurements. The fetch is the area the eddy covariance system measures where the size of the fetch can vary significantly depending on the height of the sonic anemometer. When mounted at lower heights (i.e. over shorter vegetation) the fetch area can cover from tens of meters to up to a kilometer depending on atmospheric stability (Culf et al., 2004). The fetch area is much greater over tall vegetation because sonic measurements can be taken up to 20 m above the canopy (Aubinet et al., 2000). Here, the fetch can extend several kilometers. Comparatively, the measurements for net radiation, soil heat flux, and the storage terms have much smaller footprints often only extending a few meters or even less (Culf et al., 2004; Foken, 2008).
This mismatch in footprint has been considered as a possible cause for random error in eddy covariance energy budget closure. However, in Oncley et al. (2007), an overview of EBEX-2000 is given where all terms of the energy budget equation were measured at comparable scales and it was concluded that the differences in instrument footprints had no significant impact.

1.1.1.4 Advevtive Flux Divergence

Eddy covariance calculations are based on the fundamental assumption that there is no horizontal advection of fluxes. Horizontal advection occurs over heterogeneous landscapes or complex topography when the air in equilibrium with one surface is transported horizontally to a new surface with contrasting characteristics (Foken, 2008; Harman and Finnigan, 2010; Katul et al., 2006). For accurate eddy covariance measurements there can be no horizontal advection; therefore, eddy covariance measurements need to be taken over flat, homogeneous terrain in order to comply with this fundamental assumption of the eddy covariance technique. When this assumption is not met, the presence of horizontal flux divergence may contribute to the lack of closure in the energy budget. When horizontal flux divergence is present, it is unclear what methods should be used to measure it (Aubinet et al., 2010), and attempts to estimate horizontal advection have proven to be difficult (Aubinet et al., 2005; Feigenwinter, 2004; Paw U, 2004).

There are two main reasons why horizontal flux divergence would not be able to account for the systematic underestimation of sensible and latent heat fluxes alone (Finnigan, 1999; Leuising et al., 2012). First, for horizontal flux divergence to account
for the underestimation of turbulent fluxes there would need to be unrealistically large horizontal temperature and humidity gradients (Leuning et al., 2012). Second, for the underestimation there could only be a net export of energy; however, this is not the case and horizontal advection can lead to either a net negative or positive change in energy (Finnigan, 1999; Leuning et al., 2012). Based on these studies it appears that advective flux divergence is not the main cause of the systematic underestimation of turbulent fluxes although it could be a contributing factor.

1.1.1.5 Large-Scale Turbulent Structures

Over tall vegetation, such as forests, the high aerodynamic roughness can create large-scale turbulent structures that may be too large to be detected by single tower eddy covariance measurements. The energy missed in these structures lead to systematic errors causing an underestimation of the sensible and latent heat fluxes. These large-scale eddies are often considered to be one of the main reason for poor closure (Foken, 2008) and the energy contributed by these structures can account for up to 30% of the imbalance (Finnigan et al., 2003; Leuning et al., 2012; Mauder and Foken, 2006). Evidence, which further suggests that these large-scale structures contribute to the poor closure, includes increasing averaging times (Finnigan et al., 2003; Mauder and Foken, 2006; Sakai, 2001), using wavelet analysis and airborne measurements (Mauder et al., 2007), spatially distributed measurements (Mauder, 2008), and large-eddy simulation (LES) studies (Inagaki, 2006; Kanda et al., 2004).

Typically half-hour averaging times are used in eddy covariance measurements (Leuning et al., 2012). Over tall vegetation, however, these averaging times may not be
adequate for capturing large-scale eddies (several km) as was demonstrated in Finnigan et al. (2003) and Sakai et al. (2001) when increasing the averaging time provided greater closure. In addition, wavelet analysis can be used to study the scales of turbulent fluxes and when used in combination with airborne measurements of advective fluxes, can help improve closure (Mauder et al., 2007). The large-scale eddies might also be better captured by spatially averaged measurements instead of that by a single tower, such as demonstrated in Mauder et al. (2008) where a variant of the eddy covariance method was used to measure sensible heat flux. This method captured additional sensible heat fluxes that would have been missed using traditional single tower measurements.

The contributions from large-scale eddies to energy balance closure are further supported in LES studies, such as those performed by Inagaki et al. (2006) and Kanda et al. (2004) where these structures were shown to create low-frequency trends which cannot be captured by eddy covariance. Due to limitations of the technology, LES studies cannot extend to the surface and therefore cannot identify whether large-scale turbulent structures have an effect on near-surface exchanges (Foken et al., 2011). However, a recent study by Eder et al. (2015) used three Doppler LIDARs (Light Imaging, Detection, And Ranging) to scan the surface layer and was able to find large-scale turbulent structures larger than an average 30 min scale extending deep into the surface layer. This suggests that for some eddy covariance studies conducted close to the surface, the underestimation of sensible and latent heat fluxes may be due to large-scale turbulent structures.

Even though large-scale turbulent structures may be present close to the surface, they are much less a problem over short sparse vegetation then when eddy covariance
measurements are taken from greater heights (Charuchittipan et al., 2014; Foken et al., 2006). This was shown in Foken et al. (2006) when ogive analysis was used to analyze the low-frequency range over a cornfield and found that there was no significant increase in fluxes when averaging periods were increased from half-hour to 240 minutes. Charuchittipan et al. (2014) also used ogive analysis as well as block ensemble averages to examine the effects of averaging time on closure over six land types. They found that for shorter vegetation types the half-hour averaging time was sufficient. In addition, an LES study by Steinfeld et al. (2007) found that the energy contribution of turbulent structures increased with height when they extended their LES study down to 20 m from the surface and up to the stable boundary layer. These results suggest that large-scale turbulent structures are more often an issue for eddy covariance studies over taller vegetation, than for studies where instruments are mounted a few meters above the ground.

1.1.1.6 Frequency Response Corrections

Frequency response corrections are a necessity in calculating eddy covariance fluxes, as there is an inherent loss of information due to instrument time response, sensor separation, scalar path averaging, tube attenuation, and due to signal processing choices (Moore, 1986; Massman, 2000, 2001). Often incorporated in processing software, these corrections are added to the measured fluxes to compensate for the missing data. If these corrections are neglected or improperly applied, then the eddy flux data may be incorrect (Leuning et al., 2012).
There are two main forms of frequency response corrections. The first corrects for low-pass filtering losses (high-frequency range), acquired through the instrumentation, and the second for high-pass filtering losses (low-frequency range), acquired due to finite time scales and data processing choices. For the correction of the high-frequency range, there are a variety of methods that can be used depending on whether the eddy covariance system uses a closed-path gas analyzer with long non-heated tubing, or whether it uses either a closed-path system with short heated tubing or an open path system. Closed-path systems with long non-heated tubing require additional analysis of the frequency response system before data processing (Ibrom et al., 2007; Fratini et al., 2012). The methods developed by Ibrom et al. (2007) and Fratini et al. (2012) both require measurements for the cut-off frequency of each instrument and gas in the system, and the water vapour cut-off frequency as a function of relative humidity. In addition, the Fratini et al. (2012) method also requires in situ measurement of the sensible heat co-spectra. Neither of these methods corrects for instrument separation and therefore a further correction must be applied (Horst and Lenschow, 2009). For systems with either an open path gas analyzer or a closed-path gas analyzer with short, heated tubing additional analysis of the frequency response system is not required (Massman, 2000, 2001; Moncrieff et al., 1997). For these systems, either of the analytical methods developed by Massman (2000, 2001) or Moncrieff et al. (1997) can be used.

Data is lost in the low-frequency range due to the fluxes being calculated based on a finite time period, and due to steps that were taken during data processing to ensure a relatively stationary time series. These data processing steps may include various detrending operations such as linear detrending, running mean, and non-linear filtering.
For correcting the low-frequency range of data the method developed by Moncrieff et al. (2004) can be applied.

1.1.2 Forcing Closure

To account for the imbalance problem, studies have suggested methods for forcing closure by either attributing residual energy to sensible heat flux, latent heat flux, available energy, or a combination of the above. In Twine et al. (2000) two methods were used to force closure. The first method assumes that most errors come from the latent heat flux measurements and therefore calculates the latent heat flux as a residual of the energy budget instead of what was directly measured. This method is supported by studies that have found greater closure during very dry conditions (Heusinkveld et al., 2004; Wohlfahrt et al., 2009). In both Heusinkveld et al. (2004) and Wohlfahrt et al. (2009) closure was found under almost all condition in arid desert environments (i.e. very low latent heat flux). Twine et al. (2000) also found greater closure during the drier month of August (90% closure) in comparison to June and July (80% closure).

The second method used by Twine et al. (2000) adjusts both the sensible and latent heat fluxes while conserving the Bowen-ratio. This was found to be the preferred method as discarding the measurements for latent heat flux is unfavourable when there is still uncertainty in other measurements. Jung et al. (2010) applied this method when conducting a global analysis of evapotranspiration. However, this method is limited by two major assumptions. First, there is the assumption of scalar similarity (i.e. that gases are transported in a similar way). While Pearson et al. (1998) may have found that at high frequencies there was scalar similarity between fluxes, there is evidence to suggest that at
lower frequencies they are different (Finnigan et al., 2003). Without scalar similarity the Bowen-ratio method is invalid. The second assumption is that both sensible and latent heat fluxes are equally affected by sensor limitations; however, calibration is a lot more difficult to maintain for humidity sensors than temperature sensors and therefore more likely to produce errors (Göckede et al., 2008).

Closure may need to be forced when working with either models or equations that assume closure; such is the case with the Penman-Monteith combination equation. In Wohlfahrt et al. (2009), various methods for forcing closure at half-hour averaging periods, and how they affect the calculation of surface conductance to water vapour as calculated by the Penman-Monteith combination equation, are compared. These methods include forcing closure by (1) attributing residual energy to sensible heat flux, (2) attributing residual energy to latent heat flux, (3) attributing residual energy to both sensible and latent heat fluxes while conserving the Bowen-ratio, (4) modifying sensible and latent heat fluxes to force closure on monthly time-scales while conserving the Bowen-ratio, and (5) attributing residual energy to the available energy. It was found that the value for surface conductance to water vapour varied considerably depending on the method used to force closure. Although more research needs to be done, it was found that forcing closure over longer time periods while conserving the Bowen-ratio granted better closure than when it was forced at the half-hour, as the latter resulted in some unrealistic values for the turbulent fluxes.

While forcing closure is sometimes unavoidable, such is the case in some models and equations, it is not always appealing due to our current limited understanding of what
causes the imbalance problem. Before a conclusive method for forcing closure can be made, more research needs to be done on the sources of imbalance.

1.1.3 Summary

The eddy covariance energy budget closure often has an imbalance of 10-30% (Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002). This imbalance may be caused by various instrumentation issues such as problems with the net radiation measurement, neglected or improper measurements for storage terms, or a mismatch in instrument footprints. Both net radiation issues and a mismatch in the instrument footprints are unable to account for the systematic underestimation of turbulent fluxes as both result in random errors (Oncley et al., 2007; Leuning et al., 2012). Storage terms can be a large source of systematic error when neglected from the energy budget equation leading to the overestimation of available energy (Leuning et al., 2012; Ochsner et al., 2007; Oliphant et al., 2004). The significance of each storage term, whether it is for soil, air, biomass, or biochemical, varies significantly depending on of the vegetation type. For agricultural fields or sites with sparse vegetation, the soil storage term is often the most dominant (Leuning et al., 2012; Meyers and Hollinger, 2004). Comparatively, in tall forest canopies, the storage terms for air, biomass, and biochemical are often much larger than the soil storage (Emmel et al., 2013; Leuning et al., 2012; Lindroth et al., 2010).

The presence of turbulent structures can be an issue over heterogeneous landscapes and tall vegetation (Foken, 2008). These structures may be in the form of advective flux divergence, or as large-scale turbulent structures. Advective flux divergence is unable to account for the underestimation of sensible and turbulent fluxes alone (Leuning et al.,
however, over tall canopies, large-scale turbulent structures can account for up to 30% of the imbalance (Finnigan et al., 2003; Mauder and Foken, 2006). Although there is some evidence that large-scale turbulent structures can extend far into the surface-layer (Eder et al., 2015), they are less important over shorter vegetation (Foken et al., 2006).

Frequency response corrections can be a source of error when neglected or incorrectly applied (Leuning et al., 2012). However, as long as care is taken during data processing, this should not be an issue. Various methods have been proposed for forcing closure, such as adjusting sensible and latent heat fluxes based on the Bowen-ratio for half-hour time scales and longer (Twine et al., 2000; Wohlfahrt et al., 2009). Although at times necessary, forcing closure is not the most appealing option when there is still a large amount of uncertainty in where the errors are coming from (Twine et al., 2000).
1.2 OBJECTIVES

If correct instrumentation and data processing methods are applied, and assuming that large-scale turbulent structures are only a minor issue over flat agricultural fields, then achieving energy budget closure should be possible at half-hour averaging periods. Here we aimed to improve energy budget closure through two main objectives:

1. To assess energy budget closure in a cornfield with comprehensive measurements of all energy budget components including multiple, dispersed measurements for soil heat flux and soil heat storage with heat pulse probes (HPP).

2. To test the hypothesis that least squares regression and inverse matrix analyses can be applied to sets of 24-hour energy budget data to identify areas of error.

1.3 THESIS ORGANIZATION

This thesis is divided into three main chapters. The first chapter provides background information through a literature review. The second chapter is written in manuscript form and focuses on the two main objectives. The third and final chapter provides a summary and conclusion.
CHAPTER 2: EDDY COVARIANCE ENERGY BUDGET CLOSURE

2.1 INTRODUCTION

According to the first law of thermodynamics, the incoming and outgoing energy at the earth’s surface must balance. Therefore, all incoming energy must be accounted for by either outgoing radiation, energy stored in surface materials, or transferred to deeper materials. The eddy covariance technique is often used to quantify the transfer of energy in the form of sensible ($H$) and latent heat ($LE$) between the earth’s surface and the atmosphere. Despite being one of the most accurate techniques in energy and mass flux measurements, energy budget closure has long been an issue with eddy covariance systems. The energy budget remains unclosed or unbalanced when the sum of $H$ and $LE$ do not equal the available energy. Here the available energy is the net radiation ($R_n$) minus the soil heat flux ($G$) and the heat storage terms ($\Delta S$). Past studies have shown that average energy fluxes measured by the eddy covariance technique are smaller than the available energy by $\sim$10-30% (Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002). If these fluxes are underestimated and not accurate then this may weaken studies and models using eddy covariance data such as soil-vegetation-atmosphere transfer (SVAT) models and land surface models (LSMs) (Foken et al., 2008; Williams et al., 2009).
The closure problem can be broken down into either an underestimation of the turbulent fluxes or an overestimation of the available energy. At some research sites, particularly those with tall vegetation or heterogeneous landscapes, it is known that large-scale turbulent structures have an impact on the underestimation of turbulent fluxes (Finnigan et al., 2003; Foken, 2008; Leuning et al., 2012; Mauder and Foken, 2006). This is supported by studies that have looked into increasing averaging times (Fiinigan et al., 2003; Mauder and Foken, 2006; Sakai, 2001), using wavelet analysis of airborne measurements (Mauder et al., 2007), and spatially distributed measurements (Mauder, 2008), and LES studies (Inagaki, 2006; Kanda et al., 2004). However, over shorter vegetation the lower aerodynamic roughness decreases the likelihood of large-scale turbulent structures developing. In both Foken et al. (2006) and Charuchittipan et al. (2014), it was found that half-hour averaging times were sufficient for capturing the turbulent structures present over shorter vegetation.

If turbulent structures are not the main cause of the closure problem over shorter vegetation then the overestimation of available energy is likely. The available energy can be broken down into the measurements for net radiation, soil heat flux, and the heat storage terms for soil, air, and biomass. Between different makes and models of net radiometers, there can be a difference of ~5% (Field et al., 1992; Kohsiek et al., 2007). While a difference of 5% is not enough to account for all of the lack of closure it may be a contributing factor. Soil heat flux measurements are often assumed to have low spatial variability, and therefore one or two heat flux plates are typically considered adequate for taking these measurements (Jansen et al., 2011). However, multiple studies have found spatial variation in soil heat flux measurements (Jansen et al., 2011; Tuzet et al., 1997;
Kustas et al., 2000). Tuzet et al. (1997) and Kustas et al. (2000) found that the heterogeneous shading effects of overlying canopies impacts the spatial variability of soil heat flux in the soil. Furthermore, Jansen et al. (2011) found a 100% difference in soil heat flux between two points spaced 15 m apart. Therefore, to accurately measure the soil heat flux, multiple distributed soil heat flux measurements need to be acquired. Neglecting heat storage terms can lead to an overestimation of the available energy (Leuning et al., 2012). These terms include heat storage in the soil, air, biomass, and biochemical. Since soil heat flux measurements are typically taken a few centimeters below the surface, a term for soil heat storage above this point should be included in the energy budget equation (Leuning et al., 2012; Ochsner et al., 2007; Oliphant et al., 2004). The soil storage term is particularly important under conditions of sparse vegetation or agricultural fields where large amounts of energy reach the soil surface (Leuning et al., 2012). Other heat storage terms such as those for biomass, air, and biochemical are often neglected from the energy budget (Leuning et al., 2012). Although the air and biochemical heat storage terms are small over agricultural fields and can be neglected with minimal impact (Leuning et al., 2012), the storage term for biomass can be significant especially when the canopy is fully developed (Meyers and Hollinger, 2004).

Even though various studies have researched the effects of storage terms on the energy budget of agricultural fields, they typically rely on only a few measurements for soil heat flux and soil heat storage. It is common practice for soil heat flux measurements to be taken by only one or two soil heat flux plates and for the soil storage to be estimated based on a few measurements for soil temperature and volumetric heat capacity (Jansen, et al., 2011). These methods typically do not cover a large area and therefore may not
capture heterogeneity in the soil. The main objectives of this research was to (1) further research the effect of storage terms on energy budget closure by accurately accounting for all terms in the energy budget equation over an agricultural field while incorporating an array of heat pulse probes for more soil heat flux and soil heat storage measurements and (2) to apply least squares regression and inverse matrix analyses to sets of 24-hour energy budget data to identify areas of error. This was accomplished through the collection of comprehensive and accurate data for net radiation \((Rn)\), sensible \((H)\) and latent \((LE)\) heat flux, soil heat flux \((G)\), soil heat storage \((\Delta S_s)\), air heat storage \((\Delta S_a)\), and heat storage in corn \((\Delta S_c)\).

2.2 METHODOLOGY

2.2.1 Field Site

The field site was at the University of Guelph, Elora Research Station \((43° 39'\ N, 80° 25'\ W)\) located approximately 5 km South of Elora, Ontario, Canada, at an elevation of 376 m above sea level. It consists of 650 ha of farmland, of which 120 ha is dedicated to field crop research. The field plot (Plot 2) was one of four, 1.5 ha plots that are part of a separate research project. The site had an overall flat and homogeneous topography, and was managed under conventional tillage practices with continuous corn. The experimental period occurred during the summer 2016 growing season from day of year \((DOY)\) 198-243 (July 16 – August 30). During this time the corn ranged in height from ~1.2-2.4 m. Further soil and field characteristics can be found Wagner-Riddle et al. (2007).
2.2.2 Theory

The energy budget is the balance between the sum of turbulent fluxes and the available energy as shown in Equation 2.1, where available energy is the difference between the net radiation and the soil heat flux and heat storage terms:

\[ H + LE = R_n - G - \Delta S_s - \Delta S_a - \Delta S_c , \]  

(2.1)

where \( H \) is the sensible heat flux, \( LE \) is the latent heat flux, \( R_n \) is the net radiation, \( G \) is the surface soil heat flux, and \( \Delta S_s, \Delta S_a, \) and \( \Delta S_c \) are the heat storage terms for within the top 5cm of soil, the air below the point of turbulent flux measurement and within the corn, respectively. The units for all terms in the energy budget are W m\(^{-2}\).

To calculate the sensible and latent heat fluxes from high-frequency data sets, half-hour time averages for the vertical wind component \( (w) \), temperature \( (T) \), and water vapour density \( (q) \) were measured. For each of the above components, the deviation from the mean was estimated for each record within the time interval \((w', T', q')\). The covariance between \( w' \) and \( T' \) can then be calculated to get sensible heat flux as given by Equation 2.2:

\[ H = \rho_a c_p \overline{w'T'} , \]  

(2.2)

where \( \rho_a \) is the air density (kg m\(^{-3}\)) and \( c_p \) is the specific heat of air. The covariance between \( w' \) and \( q' \) can be calculated to get latent flux as given by Equation 2.3:

\[ LE = \lambda \rho_a \overline{w'q'} , \]  

(2.3)

where \( \lambda \) is the latent heat of vaporization (J kg\(^{-1}\)).

The heat pulse probes use the principle of heat transfer through the soil to determine the soil volumetric heat capacity \((C, \text{J m}^{-3} \text{K}^{-1})\) and the thermal diffusivity \((\kappa, \text{m}^2 \text{s}^{-1})\). Equation 2.4 is a solution from Bristow et al. (1994) for a finite heat pulse when \( t > t_0 \):
\[
T(r,t) = \frac{Q'}{4\pi \kappa} \left[ Ei \left( -\frac{r^2}{4\kappa (t-t_0)} \right) - Ei \left( -\frac{r^2}{4\kappa t_0} \right) \right],
\]

(2.4)

where \( T \) is the temperature (K), \( r \) is the distance from heat source (m), \( t \) is time of initial heating (s), \( t_0 \) is the time when heating is terminated (s), \( Q' \) is the quantity of heat (m\(^2\) K s\(^{-1}\)) equal to \( q'/C \), where \( q' \) is the output from the heat source (W m\(^{-1}\)), and \( Ei \) is the exponential integral. By rearranging Equation 2.4 and making a few substitutions a solution for \( C \) can be found as given by Equation 2.5.

\[
C = \frac{q'}{4\pi \kappa \Delta T_m} \left[ Ei \left( -\frac{r^2}{4\kappa (t_m-t_0)} \right) - Ei \left( -\frac{r^2}{4\kappa t_m} \right) \right],
\]

(2.5)

where \( \Delta T_m \) is the maximum temperature change, and \( t_m \) is the time to maximum temperature change. Furthermore, by taking the derivative of Equation 2.4 with respect to time a solution for \( \kappa \) is found (Equation 2.6).

\[
\kappa = \frac{r^2}{4} \left[ \frac{1}{\ln \left( \frac{t_m-t_0}{t_m} \right)} \right],
\]

(2.6)

Values for \( C \) and \( \kappa \) can be used to determine a solution for \( G \), the soil heat flux (W m\(^{-2}\)) (Equation 2.7):

\[
G = -\kappa C \left( \frac{\partial T}{\partial z} \right),
\]

(2.7)

where \( \frac{\partial T}{\partial z} \) is the change in temperature (K) with depth (m). And for \( \Delta S_z \), the soil heat storage (W m\(^{-2}\)) as given by Equation 2.8:

\[
\Delta S_z = C \left( \frac{\partial T}{\partial t} \right) \Delta z,
\]

(2.8)

where \( \frac{\partial T}{\partial t} \) is the change in temperature (°C) with time, \( t \) (s), and \( \Delta z \) is the distance between needles (m).
Values for heat storage in the air below the point of turbulent flux measurement, $\Delta S_a$ (W m$^{-2}$), were calculated using Equation 2.9:

$$\Delta S_a = \rho_a c_{pa} \frac{\Delta T_a}{\Delta t} \Delta z,$$

(2.9)

where $c_{pa}$ is the specific heat of air (J kg$^{-1}$ K$^{-1}$), $\Delta T_a$ is the change in air temperature (K), $\Delta t$ is the change in time (s), and $\Delta z$ is the distance between the sonic anemometer and the ground (m). Equation 2.10 was used to calculate heat storage in crops, $\Delta S_c$ (W m$^{-2}$):

$$\Delta S_c = bio c_{pw} \frac{\Delta T_c}{\Delta t},$$

(2.10)

where $bio$ is the biomass of corn (kg m$^{-2}$), $c_{pw}$ is the specific heat of water (J kg$^{-1}$ K$^{-1}$), $\Delta T_c$ is the change in crop temperature (K), and $\Delta t$ is the change in time (s).

2.2.3 Field Setup and Instrumentation

Conventional eddy covariance practices, including a closed-path eddy covariance system (model CPEC200, Campbell Scientific, Inc. (CSI), Logan, Utah, USA), were used to measure $H$ and $LE$ in plot 2. The eddy covariance system consisted of a closed-path gas analyzer (model EC155, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) to measure water vapour and other trace gases and a sonic anemometer (model CSAT3, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) to measure orthogonal wind components and air temperature. The eddy covariance system recorded high-frequency (10 Hz) data that was sent to a data logger for storage (model CR3000, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) and downloaded in situ weekly.

A net radiometer (model NR-Lite 2, Kipp & Zonen, Inc., Delft, The Netherlands) was installed in Plot 2 on a tower protruding south over the cornfield. The net radiometer was attached to a boom before being attached to the tower at a height of 4 m. Net radiation
measurements were taken every 30 s and half-hour averages were stored on a data logger (model 21X, Campbell Scientific, Inc. (CSI), Logan, Utah, USA).

Two methods were used to measure air heat storage below the flux measurement point. The first used the air temperature measured by the sonic anemometer to estimate the air storage below the measurement point. Simultaneously, an array of eight fine-wire thermocouples logarithmically spaced within and above the corn measured the air temperature profile below the sonic anemometer. The eight thermocouples were wired to a data logger (model CR5000, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) and were stored in tables before being converted into values for air storage. Due to the delicate nature of the fine-wire thermocouples, they were prone to breaking. This lead to data only being available for part of the experimental period.

An array of twelve heat pulse probes (HPP) was installed in Plot 2 to measure soil heat flux \((G)\) and four were installed to measure soil heat storage \((\Delta S_s)\). The probes consisted of two thermistor needles surrounding a center heater needle all of which was encased in a resin (Bristow et al., 1994, Campbell et al., 1991). The center heater needles were wired to an AC/DC relay controller (model SDM-CD 16AC, Campbell Scientific, Inc. (CSI), Logan Utah, USA), and the thermistor needles were wired to a relay multiplexer (model AM16/32B, Campbell Scientific, Inc. (CSI), Logan, Utah, USA). The relays were both controlled by a data logger (model CR1000, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) where the data tables for the HPP were also stored.

For the soil heat flux measurements, the 12 probes were installed by digging five shallow trenches in between the rows of corn with 2-3 HPP allotted to each. The probes were then inserted horizontally into the sidewalls of each trench at a depth of 5 cm. The
removed soil was used to refill each trench and was firmly packed down. For the soil heat storage measurements, the probes were inserted vertically into the soil to measure the heat storage in the top 5 cm of soil above the horizontal HPP. For comparison, two soil heat flux plates (HFP) (Campbell Scientific, Inc. (CSI), Logan, Utah, USA) were installed horizontally in the soil at a 5 cm depth and a second data logger (model CR1000, Campbell Scientific, Inc. (CSI), Logan, Utah, USA) was used to record the soil heat flux every 15 minutes.

Attached to the same data logger as the HFP, auxiliary measurements for a soil temperature profile were collected by an array of twenty-four thermocouples. To measure the soil temperature profile, four pits were dug and six thermocouples were inserted into each sidewall at 2, 5, 10, 15, 20, and 25 cm depths, respectively. In addition, two downward facing infrared thermometers measured soil surface temperature from about 30 cm above the soil. Another two infrared thermometers were used to measure the crop temperature. These were installed at a height of ~1.5 m and were angled towards the crops. Crop temperature data along with biweekly measurements for biomass (Dr. Aaron Berg, personal communication, 2016) were used to calculate crop heat storage ($\Delta S_c$). All four of the infrared thermometers were wired to the same data logger as the HFP where their data tables were saved and collected in situ weekly.

Hourly climate data was collected at the Elora Weather Station located within the Elora Research Station: air temperature, relative humidity, wind direction/speed (2 m and 10 m), incoming solar radiation, and incoming longwave radiation, precipitation, and amount of sunshine. This station is maintained through the collaboration of Environment Canada and the University of Guelph, School of Environmental Sciences.
2.2.4  *Eddy Covariance Data Processing*

Various corrections must be applied to the high-frequency raw eddy covariance data. In this study, most data corrections were applied using EddyPro Software (Version 6, LI-COR, Inc., Lincoln, NE, USA). One such correction was axis rotation, which corrects for any misalignment of the sonic anemometer with the mean streamline wind at the field site. Data despiking was done to remove noise and anomalies from the dataset. Time lag compensations were applied to the data to correct for lag from the closed-path gas analyzer due to the viscosity of gases in the intake tube. Detrending flux data was done to remove any superimposed low-frequency trends caused by a lack of steady state conditions in the atmosphere. Spectral corrections were required to correct for data losses from flux processing choices, and instrument setup and design. Other post-processing involved filtering for times of low turbulence and for when the intakes were taken out of the field. These filters were applied using MATLAB (version R2013a, The MathWorks, Inc., Natick, Massachusetts, USA).

2.2.5  *Data Analysis*

A set of 24-hours worth of half-hour average energy budget data forms an over-determined set of linear equations as depicted below:

\[
\begin{bmatrix}
R_{n_1} \\
R_{n_2} \\
\vdots \\
R_{n_{48}}
\end{bmatrix}
= 
\begin{bmatrix}
H_1 + LE_1 + G_1 + \Delta S_{s_1} + \Delta S_{a_1} + \Delta S_{c_1} \\
H_2 + LE_2 + G_2 + \Delta S_{s_2} + \Delta S_{a_2} + \Delta S_{c_2} \\
\vdots \\
H_{48} + LE_{48} + G_{48} + \Delta S_{s_{48}} + \Delta S_{a_{48}} + \Delta S_{c_{48}}
\end{bmatrix}
\]  

(2.11)
Least squares regression and inverse matrix analysis were applied to this over-determined system to solve for a coefficient for each term. These coefficients were hypothesized to indicate how accurately each of these terms were measured and whether they are over- or underestimated. For example, a coefficient less than one would indicate overestimation, while a coefficient greater than one would indicate underestimation. This process was applied in MATLAB as follows:

\[
[Co] = [Matrix] \backslash [R_n]
\]  

(2.12)

where \( Co \) is an array of coefficients, one for each of the terms in the energy budget equation except for net radiation, and the \( \backslash \) is an operator in MATLAB for matrix division. As well as being applied to individual days of data, the least squares regression and inverse matrix analysis were also applied to composite days for the entire study period (DOY 198-243) and for July and August, separately.

2.3 RESULTS

2.3.1 Component Partitioning

Composite daily patterns of the half-hour averages for net radiation, sensible heat flux, latent heat flux, soil heat flux, soil heat storage, air heat storage, and crop heat storage for DOY 198 to 243 (July 16\textsuperscript{th} – Aug 31\textsuperscript{st}) are plotted in Figure 2.1 to show how the energy balance components are partitioned. The maximum peak of net radiation occurs just before noon at approximately 550 W m\textsuperscript{-2}. After peaking there is a noticeable dip in the net radiation occurring around midday. This dip corresponds with a dip in the latent heat flux, yet does not correlate with any of the other components.
In Figure 2.1, the remaining energy budget components can be compared to net radiation. It is shown that latent heat flux accounts for the greatest amount of the available energy peaking at around 300 W m\(^{-2}\), higher than all other components except for net radiation. After peaking there is a slight dip in the early afternoon, correlating with the dip in net radiation. A significant lag between the net radiation and the latent heat flux can be seen, with the latent heat flux peaking later in the day and lagging throughout the evening. Throughout most of the early morning and at night the latent heat flux remains positive but never greater than \(\sim 20\) W m\(^{-2}\).

After latent heat flux, sensible heat flux accounts for the next greatest amount of the available energy. In comparison to latent heat flux, sensible heat flux was much more sensitive to changes in net radiation and therefore there was no noticeable lag between the two. In Figure 2.1, sensible heat flux peaks at around the same time as the net radiation at a maximum of \(\sim 175\) W m\(^{-2}\). Unlike the net radiation, there is no noticeable dip around midday. In the evening, sensible heat flux slightly precedes net radiation falling below zero earlier and remaining negative for the rest of the evening and early morning.

Similar to latent heat flux, the soil heat flux as measured by the HPP, lags behind the net radiation. The soil heat flux reaches a maximum peak after net radiation at approximately 60-70 W m\(^{-2}\). At night the soil heat flux drops below zero, although remains above net radiation. Comparatively, the soil heat storage measured above the soil heat flux measurements, peaks earlier in the morning. When net radiation decreases in the afternoon, the soil heat storage decreases and drops below zero. Throughout the early morning and in the late afternoon and evening, the soil heat storage remains negative.
Crop heat storage follows a similar pattern to soil heat storage where it peaks early in the morning at about 25-30 W m$^{-2}$ before dropping below zero once net radiation begins to decrease. As with soil heat storage, crop storage remains below zero in the evening. In addition, air storage follows a similar pattern, however, values were on average less than 1% of net radiation and therefore, negligible.

![Composite half-hour diurnal plot of net radiation ($R_n$), sensible heat flux ($H$), latent heat flux ($LE$), soil heat flux ($G$), soil heat storage ($\Delta S_s$), air heat storage ($\Delta S_a$) and crop heat storage ($\Delta S_c$) for DOY 198 – 243. Error bars are the standard error of the mean.](image)

In Figure 2.1 there was a midday drop in net radiation that did not correspond with any of the other energy budget components except for a slight dip in latent heat flux. However, other net radiometers installed in the field observed the same decrease in net radiation. It was found that this drop was due to a few days in August when net radiation decreased around noon. These midday drops are seen in Figure 2.2 where the half-hour diurnal plots for August 3$^{rd}$, 5$^{th}$, 7$^{th}$, and 23$^{rd}$, are shown respectively. In Figure 2.2, all
four days show the net radiation corresponding well with the sensible and latent heat fluxes. In panels (a), (b), and (c), the turbulent fluxes can be seen decreasing at midday coinciding with changes in the net radiation on the 3rd, 5th and 7th.

Figure 2.2 Half-hour diurnal plots for net radiation \( (R_n) \), sensible \( (H) \), latent \( (LE) \), and soil \( (G) \) heat flux, soil heat storage \( (\Delta S_s) \), air heat storage \( (\Delta S_a) \) and crop heat storage \( (\Delta S_c) \) for August (a) 3rd, (b) 5th, (c) 7th, and (d) 23rd.

2.3.2 Energy Budget Closure

Half-hourly data from the Elora Research Station was used to examine the effect of storage terms on the surface energy budget. Sensible and latent heat fluxes \( (H + LE) \) were compared to the available energy \( (R_n - G) \), with and without the storage terms subtracted for DOY 198 to 243. In Figure 2.3 (a), the turbulent fluxes are plotted against available
energy without the storage terms for soil, air, and biomass ($\Delta S_s$, $\Delta S_a$, $\Delta S_c$). Here the slope from linear regressions is less than one at 0.90 with an intercept greater than zero at 12.50 ($R^2 = 0.92$, p-value < 0.05). In Figure 2.3 (b), the storage terms are included in the available energy (i.e. $R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$). The inclusion of the storage terms improves unity, moving the slope from the linear regression closer to one at 0.99 and the intercept closer to zero at 2.46 ($R^2 = 0.93$, p-value < 0.05). In addition, $t$-tests also show that the slopes are significantly different (p-value < 0.05).

The largest storage term is the heat storage in the soil, which accounts for approximately 10% of the net radiation. The storage terms for biomass and air are much smaller, however, they still have an impact on storage. Without these terms in the budget, the slope from linear regression is slightly lower at 0.97 and the systematic bias remains a bit higher with the intercept at 3.77 (p-value < 0.05).

Panels (c) and (d) of Figure 2.3 show half-hourly data for turbulent fluxes and available energy combined into composite 24-hour days. Panel (c) corresponds to panel (a) of Figure 2.3 where the storage terms have been ignored. When the storage terms are not subtracted from the available energy a phase lag between $H + LE$ and $R_n - G$ is apparent. Throughout the day, the available energy precedes the sum of the turbulent fluxes, coming to greater values in the morning, peaking higher around noon, and falling below $H + LE$ at night. Panel (d) corresponds to panel (b) of Figure 2.3 where the storage terms for soil, air, and biomass have been considered. By subtracting the storage terms from the available energy, the agreement between the sum of the turbulent fluxes and the available energy greatly improves. In addition, storage terms bring the peak for $R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$ down to where it is comparable to that of the turbulent fluxes.
Figure 2.3 (a) & (b) Scatterplots of turbulent fluxes \((H + LE)\) versus available energy \((Rn - G)\) with and without storage terms, respectively) for half-hourly-averaged measurements at Elora Research Station. Panels (c) & (d) show the corresponding composite diurnal plots for DOY 198 to 243 where error bars are standard error of the mean.

2.3.3 Daily Closure

To compare daily variation in energy budget closure, values for daily closure obtained through the slope of linear regression of the turbulent fluxes \((H + LE)\) and the available energy \((Rn - G - \Delta S_s - \Delta S_a - \Delta S_c)\) were plotted in Figure 2.4. The majority of the values for daily closure fell within 10% of full closure, where full closure is 1.0 (i.e. between 0.9 and 1.1). Near the end of July, there are a few days where energy budget closure falls below 0.8. These days are July 29th, 30th, and 31st where closure values were approximately 0.75, 0.77 and 0.72, respectively. In addition, near the end of August on the 27th, the daily closure value dropped to 0.69. Preceding both of these low closure
events there were days of heavy rainfall. On July 25\textsuperscript{th} there was 36 mm of rainfall with light rain the two following days, and on August 25\textsuperscript{th}, there was greater than 30 mm of rainfall (rain data obtained from the Elora Research Station).

In Figure 2.5, the four days mentioned previously where daily closure fell below 0.8 are shown as partitioned diurnal plots. Due to increased soil moisture following heavy rainfall, greater amounts of latent heat flux were anticipated. However, the amount of latent heat flux appears to be either about average (peaking around 300 W m\textsuperscript{-2}) or below in comparison to Figure 2.1.

![Graph showing daily closure values for energy budget closure](image_url)

*Figure 2.4 Values for energy budget closure obtained through the slope of linear regression for DOY 198 to 243 where error bars are the standard error of the mean.*
Figure 2.5 Half-hour diurnal plots of net radiation ($R_n$), sensible ($H$), latent ($LE$), and soil ($G$) heat flux, soil heat storage ($\Delta S_s$), air heat storage ($\Delta S_a$) and crop heat storage ($\Delta S_c$) for July (a) 29th, (b) 30th, (c) 31st, and (d) August 27th.

2.3.4 Energy Budget Closure and Turbulent Fluxes

Figure 2.6 shows the relationship between values for daily energy budget closure obtained through linear regression and total accumulated daily latent heat flux (i.e. daily sum). An $R^2$ value of 0.39 and a p-value less than 0.05, indicates that the latent heat flux accounts for 39% of the variability in daily closure. When the daily closure was plotted against sensible heat flux there was no significant ($R^2 < 0.1$, p-value > 0.05) relationship found. This was surprising as sensible and latent heat flux correlate on half-hourly time scales as shown in Figure 2.7 where there is an $R^2$ value of approximately 0.58 (p-value < 0.05). Due to this correlation, one might expect the sensible heat flux to have a
relationship with daily closure. However, Figure 2.6 uses total daily latent heat flux, not half-hour data. When comparing the daily totals for the turbulent fluxes there was no significant relationship found. Figure 2.8 shows the negative relationship between the residuals from the regression of daily closure and $LE$ from Figure 2.6 and the variance of HPP $G$ ($R^2 = 0.37$). With higher variance in the HPP $G$ measurements the more negative the residuals. Here higher variance $G$ indicates greater soil heterogeneity.

Figure 2.6 Scatterplot of daily closure values obtained through linear regression versus the total accumulated daily latent heat flux ($LE$) for DOY 198-243.
Figure 2.7 Scatterplot of latent heat flux (LE) versus sensible heat flux (H) for DOY 198-243.

Figure 2.8 Scatterplot of residuals from daily closure and latent heat flux (LE) regression versus HPP soil heat flux (G) variance.
2.3.5 *Soil Heat Flux*

This study used an array of 12 heat pulse probes (HPP) to measure the soil heat flux, and 4 HPP to measure soil heat storage ($\Delta S_s$) in the top 5 cm of the soil. It is common practice in energy budget studies to use only one or two heat flux plates (HFP) to measure the soil heat flux. In comparison, by using an array of HPP, a larger footprint on the scale of meters, instead of centimeters, was measured allowing for greater soil heterogeneity to be captured. When individual HPP were compared, variability > 20% was found between probes located 3 m apart.

In Figure 2.9, soil heat flux ($G$) as measured by the HPP is compared to that measured by the HFP demonstrating that they are comparably accurate and that the HPP are a viable option for measuring soil heat flux and soil heat storage ($\Delta S_s$) in the field. When linear regression is applied to the data, the resulting slope is close to unity at 0.97 and the intercept is close to zero at 0.06 Wm$^{-2}$ ($R^2 = 0.86$, p-value < 0.05). Therefore, average soil heat flux as calculated by HPP is comparable to that calculated by the HFP. It should be noted that there was a relatively large root mean square error (RMSE) value of 11.32 and greater scattering when $G$ is at its highest.

To compare how the $G$ measured by the HFP effects the overall energy budget in comparison to that measured by the HPP, Figure 2.10 (a) shows a scatterplot of $H + LE$ versus $R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$, where $G$ is the soil heat flux measured by the HFP. In comparison to when the $G$ from the HPP was used in panel (b), energy budget closure was less using the HFP. In panel (b), the slope from linear regression was ~0.99 with an intercept of 2.46 and an $R^2$ value of 0.93 (p-value < 0.05), while when the HFP were used in Figure 2.10, the slope was ~0.96, an intercept of 3.30 and an $R^2$ value of 0.92 (p-value
< 0.05). In addition, a t-test was done to show that the slopes are significantly different. Comparing panels (c) and (d) of Figure 2.10 shows that the G measured by the HFP does not bring the available energy to level similar to that of the sum of turbulent fluxes. Instead, the available energy is brought below the turbulent fluxes around noon and remains higher in the afternoon.

Figure 2.11 shows the diurnal plots for the partitioned energy budget components where in (a) G is measured using HPP and in (b) it is measured using HFP. In both cases soil heat flux lags behind net radiation, peaking at about 50 Wm$^2$ around noon, and falling below zero in the evening. Comparatively, G measured by HFP peaks earlier in the day and falls sooner than that of the HPP, capturing less energy.

![Figure 2.9 Scatterplot of mean G measured by the HPP versus mean G measured by HFP for data collected from the Elora Research Station.](image)
Figure 2.10 (a) Scatterplot of turbulent fluxes (H + LE) versus available energy ($R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$, where G is from HFP), (b) scatterplot of turbulent fluxes (H + LE) versus available energy ($R_n - G - \Delta S_s - \Delta S_a - \Delta S_c$, where G is from HFP) and (c) & (d) are the corresponding diurnal plot where error bars are the standard error of the mean.
Figure 2.11 Composite diurnal plots with partitioned energy budget terms for DOY 198-243 where (a) is $G$ measured using the HPP and (b) has $G$ measured using the HFP. Error bars are the standard error of the mean.

2.3.6 Air Heat Storage

For the majority of the season, the sonic temperature was used to calculate heat storage in the air below the sonic anemometer. In late July and early August, there was also an air temperature profile consisting of 8 fine-wire thermocouples used. The two methods for measuring air heat storage are shown in Figure 2.12 where the sonic temperature overestimates air heat storage by almost 50% as indicated by the slope from linear regressions. This is due to the assumption that air temperature is constant throughout the layer below the sonic anemometer; however, within the canopy there are cooler layers as was captured by the fine-wire thermocouples.
Figure 2.12 Scatterplot of air storage calculated from the air profile versus air storage calculated from the sonic temperature.

2.3.7 Least Squares Regression and Inverse Matrix Analysis

The results from the least squares regression and inverse matrix analysis for the composite days (one for DOY 198-243, one for July, and one for August) are shown in Table 2.1. Based on these results, the coefficient for sensible heat flux was consistently greater than one. This would indicate that on average sensible heat flux was underestimated. Comparatively, the coefficient for latent heat flux was on average below one, indicating that it was overestimated. The results for soil heat flux were all within 10% of one, which could indicate that we are getting rather accurate measurements. There was a lot more variability with the results for the storage terms. For soil heat storage the results indicate that it was overestimated by ~40-55%. The air storage was
largely underestimated although rather variable. The results for crop storage was the most variable ranging from being underestimated by more than double in July to ~33% overestimated in August.

Table 2.2 shows the results of the least squares regression and inverse matrix analysis for multiple days in July and August. Note, that since this analysis required complete sets of 24-hour data, the latent heat flux values used were not filtered for times of low turbulence; however, diurnal data were plotted to check for any spikes or unrealistic values. The results for sensible and latent heat flux were similar to those found in Table 2.1 for the composite days, where it was found that sensible heat flux was underestimated and latent heat flux was overestimated. The results for soil heat flux were a lot more variable for the individual days than with the composite days, ranging from 80% overestimation to 40% underestimation. The results for soil heat storage were much lower than before, indicating that it was largely overestimated. Similarly, the air heat storage and crop heat storage were quite variable.

Table 2.1 Results from least squares regression and matrix analysis for composite daily data for DOY 198-243, July and August.

<table>
<thead>
<tr>
<th>Variable</th>
<th>DOY 198–243</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>1.88</td>
<td>1.20</td>
<td>2.00</td>
</tr>
<tr>
<td>$LE$</td>
<td>0.729</td>
<td>0.980</td>
<td>0.565</td>
</tr>
<tr>
<td>$G$</td>
<td>0.902</td>
<td>0.932</td>
<td>0.979</td>
</tr>
<tr>
<td>$\Delta S_g$</td>
<td>-0.442</td>
<td>0.529</td>
<td>-0.603</td>
</tr>
<tr>
<td>$\Delta S_a$</td>
<td>-3.43</td>
<td>-11.8</td>
<td>4.54</td>
</tr>
<tr>
<td>$\Delta S_c$</td>
<td>1.79</td>
<td>2.70</td>
<td>0.675</td>
</tr>
</tbody>
</table>
Table 2.2 Results from least squares regression and inverse matrix analysis for multiple days in July and August.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>2.18</td>
<td>1.60</td>
<td>1.02</td>
<td>1.14</td>
<td>1.05</td>
<td>0.902</td>
<td>1.42</td>
<td>1.33±0.169</td>
</tr>
<tr>
<td>$LE$</td>
<td>1.11</td>
<td>0.865</td>
<td>0.996</td>
<td>0.958</td>
<td>1.01</td>
<td>0.812</td>
<td>0.772</td>
<td>0.931±0.045</td>
</tr>
<tr>
<td>$G$</td>
<td>0.763</td>
<td>0.952</td>
<td>1.17</td>
<td>0.892</td>
<td>0.575</td>
<td>1.84</td>
<td>1.45</td>
<td>1.09±0.164</td>
</tr>
<tr>
<td>$\Delta S_e$</td>
<td>0.516</td>
<td>0.036</td>
<td>0.238</td>
<td>0.073</td>
<td>0.363</td>
<td>0.125</td>
<td>-0.660</td>
<td>0.099±0.142</td>
</tr>
<tr>
<td>$\Delta S_a$</td>
<td>-10.8</td>
<td>3.99</td>
<td>0.730</td>
<td>-0.378</td>
<td>3.51</td>
<td>2.01</td>
<td>-5.88</td>
<td>-0.979±1.93</td>
</tr>
<tr>
<td>$\Delta S_c$</td>
<td>2.59</td>
<td>0.415</td>
<td>0.963</td>
<td>1.47</td>
<td>0.455</td>
<td>1.11</td>
<td>5.24</td>
<td>1.75±0.644</td>
</tr>
</tbody>
</table>

2.4 DISCUSSION

Comprehensive measurements for all terms in the eddy covariance energy budget equation were measured. The data was analyzed by partitioning the energy budget components into composite days, by applying linear regression to the energy budget data and to the closure data with various variables, various instrumentation techniques were compared, and finally least squares regression and inverse matrix analysis was applied to 24-hour sets of data. The results from these analyses are discussed below.

2.4.1 Component Partitioning

Over saturated soils or vegetated surfaces, latent heat flux is typically the dominant energy budget component, due to water being available for this process (Timouk et al., 2009). This was shown to be the case in Figure 2.1 where the latent heat flux was on average double that of the sensible heat flux. In comparison, it is common for sensible heat to be dominant over bare soils that dry out quickly (Timouk et al., 2009). At night, sensible heat flux drops below zero with the net radiation due to surface cooling, while some latent heat flux remains. The amount of latent heat flux is not dependent on net radiation alone; hence at night the latent heat flux is influenced by the relative humidity,
the amount of turbulence, and the surface area exposed. When combined, the sensible and latent heat fluxes at the site accounted for ~80% of the net radiation on average. Of the ~80%, the latent heat flux accounted for ~50% and the sensible heat flux for ~30%.

Although the soil heat flux lags the net radiation, it is corrected through the inclusion of the soil heat storage. As seen in Figure 2.1, the soil heat storage peaks in the morning well before that of the soil heat flux. When added to the soil heat flux, the lag with net radiation is adjusted. When combined, the soil heat storage and soil heat flux can account for up to ~100 W m\(^{-2}\) or ~20% of the net radiation. This agrees with the literature where soil heat flux typically accounts for ~10% of the available energy (Culf, et al., 2004). Similarly, the soil heat storage also accounts for approximately 10% of the net radiation (Meyers and Hollinger, 2004).

In comparison to the previous energy budget terms, the storage terms for biomass and air are much smaller. On average, the energy stored in the corn accounts for approximately 2.5% of the net radiation, while the air storage accounts for less than 1%. Although in this case these terms are rather small, they become much more significant over taller canopies and denser canopies, such as over forests, where there would be much more heat storage within the trunks of trees and a thicker air layer.

When the energy budget components are partitioned into a composite 24-hour day, a noticeable drop in net radiation occurs around noon. This was likely due to midday cloud cover occurring over multiple days in August (Figure 2.2). This same dip in net radiation was observed by other net radiometers installed close by. Furthermore, since the days where net radiation dropped at midday do not occur consistently, and since appropriate
precautions were taken during instrument setup, it is concluded that the drop is not due to any shadowing over the instrument, but from natural phenomena.

2.4.2 Energy Budget Closure

From DOY 198 – 243, turbulent fluxes and available energy were in agreement. The inclusion of storage terms was important for obtaining this closure. Not only can they account for greater than 10% of the available energy, but they also correct for the lag between the net radiation and turbulent fluxes (Figure 2.3). Of the storage terms, the soil storage is the most significant usually accounting for over 8% of the net radiation. Although much smaller, including the terms for energy storage in the corn and in the air layer below the sonic height improved closure. When included in the energy budget, the slope from linear regression increased closer to unity and the systematic bias decreased as the intercept moved closer to zero.

Similar closure values have been found by past studies with comparative field conditions. In Meyers and Hollinger (2004), they closed the half-hour energy budget within 6% after including storage terms for soil, air and corn, and a term for photosynthesis. They found that these storage terms combined accounted for up to 14% of the net radiation. Leuning et al. (2012) did a comprehensive analysis of energy budget closure and found that closure is possible at half-hour timescales when storage terms are included, and when data is processed correctly. Furthermore, they found that increased instances of closure were found when daily averages were used instead of half-hour. When they applied data to daily-averaged measurements they found closure within 3%.
2.4.3 Daily Closure

The values for daily energy budget closure, obtained through linear regression, were quite variable. Despite this variability, the majority of the points were within 10% of full closure (Figure 2.4). On average, latent heat flux comprised ~50% of the net radiation and the sensible heat flux ~30%; variation in this amount was likely dependent on how dry the conditions were. For example, following a heavy rainfall, there would be increased soil moisture and as a consequence, there would typically be an increase in latent heat flux (accounting for > 60% of closure). However, in Figure 2.4, the points less than 80% of full closure are all exceptions to this. Despite following days of heavy rainfall, the amount of latent heat flux recorded was less than average. On July 25th there was 36 mm of rainfall with minor rainfall (2 mm or less) the two following days. Surprisingly, the three following days (July 29th, 30th, and 31st) experienced below average latent heat flux, with the latent heat flux accounting for 40%, 36%, and 28% of the available energy, respectively. In addition, the sensible heat fluxes on these days were slightly below average ranging from 23-27% of closure. On July 30th and 31st, the soil heat flux and soil heat storage were both approximately average, however, on the 29th, the soil heat storage was well below average only accounting for 3%.

During rainfall, there is large uncertainty in the latent heat flux measurements and consequently, these days should be excluded from any data analysis. Following rainfall, there is typically an increase in humidity, which may further lead to errors in the latent heat flux measurements. When humidity is high, the attenuation of water in the sample tube of closed-path gas analyzers is higher (Kidston et al., 2010). This leads to a dampening of the high-frequency data for the water vapour mixing ratio. Although
corrections for this are applied during data processing (i.e. time lag compensation) it may still be a possible explanation for the below average latent heat flux.

Additionally, there were lower than usual winds during this period. When there are lower winds there is also a lower frictional wind velocity. Frictional velocity is known to have an impact on turbulent fluxes measured by eddy covariance (Barr et al., 2006; Frassen et al., 2010). When the frictional velocity is low, there is an increase in measurement errors for turbulent fluxes (Barr et al., 2006; Frassen et al., 2010). Therefore, lower wind speeds may have caused measurement errors in the latent heat flux measurements leading to lower closure during this period.

When soil moisture is high, the thermal conductivity of soil increases as well as heat storage. However, on July 29th, the soil heat storage was abnormally low, only accounting for 3% of the net radiation. The soil heat flux was around 8% of the net radiation; therefore an increase in soil heat flux cannot explain the lower soil heat storage. If the latent heat was underestimated due to increased humidity or measurement errors due to low winds then perhaps an increase in latent heat flux from soil could explain the low heat storage.

2.4.4 Energy Budget Closure and Turbulent Fluxes

Total daily latent heat flux was found to account for just under 40% of the variability of the daily closure as shown in Figure 2.6. Comparatively, there was no relationship found with sensible heat flux. This may imply that there are more measurement errors in the latent heat flux than with sensible heat flux. It is also interesting to note that residual analysis of Figure 2.6 showed that there was a negative relationship between the residuals
of HPP $G$ variance as shown in Figure 2.8. This may indicate that spatial variability in soil heat flux measurements may have an impact on latent heat flux. If there are more errors with the latent heat flux measurements then it is possible that the latent heat flux measurements are a cause of underestimation in energy budget closure. Twine et al. (2000) discussed the possible issues with latent heat flux after finding that drier conditions at one of their study sites brought better energy budget closure. However, at that site, there was little confidence that the measurements for sensible heat flux were accurate and therefore did not conclude that the latent heat flux was the main issue.

If latent heat flux is a cause for error than greater closure would be expected over dry sites where sensible heat flux dominates (Heusinkveld et al., 2004; Wohlfahrt et al., 2009). This was found in both Heusinkveld et al. (2004) and Wohlfahrt et al. (2009) when closure was obtained over a very flat, homogenous and dry desert sites. This further supports that measurements for sensible heat flux may be less prone to error than those of latent heat flux. Mauder et al. (2007) also ran an experiment over a flat, homogeneous, desert site and closed the energy budget to within 5%. However, that experiment covered the change in seasons from dry to wet. Unfortunately, they only reported closure for over the entire period and did not compare between seasons. A comparison between the wet and dry seasons would have shown if there was a difference in average closure when sensible heat flux was dominant compared to latent heat flux. Since this was not the case, it cannot be concluded whether greater closure is seen over flat homogeneous desert sites due to the ideal topography or if it is due to fewer errors from latent heat flux.

If comprehensive measurements of all energy budget components, including quality measurements for all storage terms, are taken and the energy balance remains unclosed,
perhaps the issue is with the latent heat flux measurement alone. After noting better
closure during dry periods, Twine et al. (2000) suggested that the energy budget could be
forced closed by calculating the latent heat flux as a residual of the energy budget
equation.

The apparent underestimation of sensible and latent heat fluxes has led to concerns
that other turbulent fluxes may be underestimated as well. For example, if the CO₂ flux is
also underestimated then this could hamper the accuracy of models using these data.
However, if the problem does not lie with all turbulent fluxes measured by the eddy
covariance technique, but only with latent heat, then this may not be a problem.

2.4.5 Soil Heat Flux

The spatial variability of soil heat flux can be significant (Jansen et al., 2011; Tuzet et al.,
1997; Kustas et al., 2000). Therefore, by taking more measurements for soil heat flux
using the heat pulse probes the footprint of these measurements is increased from
centimeters to meters allowing for more heterogeneity in the soil to be measured and
increasing the accuracy of the soil heat flux measurements. The heat pulse probes were
also used to take soil storage measurements in the top 5 cm of the soil. Most energy
budget studies use only one soil moisture probe to measure the soil heat capacity and pair
them with a couple thermocouples to estimate the soil heat storage (Meyers and
Hollinger, 2004). Therefore, the heat capacity measurement may not be taken in the same
location as the temperature. Since each heat pulse probe measures soil heat capacity and
temperature individually, these measurements are guaranteed to pair well together.
In comparison to the heat flux plates, the heat pulse probes captured more energy in the afternoon and evening. As a result using HFP soil heat flux in the energy budget left an overestimation of available energy at these times. Additionally, the HFP soil heat flux peaked higher in the morning, so when subtracted from the available energy the resulting total was lower than the turbulent fluxes before noon.

2.4.6 Air Heat Storage

Two methods for measuring air heat storage below the sonic anemometer were used. It was found that using a profile of fine wire thermocouples accounted for more energy than estimating the storage based on the sonic temperature. Although the thermocouple profile comparatively captured more energy, the total air storage was still found to be negligible as is often the case over agricultural field sites. In addition, photosynthesis was not included in the observations as it is typically negligible over agricultural field sites and more prominent over forests and denser vegetation (Leuning et al., 2012).

2.4.7 Least Squares Regression and Inverse Matrix Analysis

The results from the least squares regression and inverse matrix analysis were inconclusive, as it was determined that most of the results were either unrealistic or too variable. The most unrealistic result was that for soil heat storage, which based on the composite day analysis, determined it to be overestimated by over 40%, and for the single day analysis, it was on average overestimated by almost 70%. This adjustment would change the soil storage in the top 5 cm of soil to on average peak at either 34 W m$^{-2}$ or 18 W m$^{-2}$, accounting for only ~5% and ~3% of the available energy, respectively. These
values are lower than what is typically seen in agricultural cornfields, where soil storage typically accounts for ~10% of the available energy (Meyers and Hollinger, 2004). A large amount of variability in some of the other results also casts doubt on this analysis. The results for soil heat flux had a large amount of variability, ranging from 80% underestimated to 40% overestimated. Since we are confident in our measurements for soil heat flux, as the HPP compared reasonably well to the HFP, this variability is spurious. In addition, there was also a large amount of variability in the results for air storage; however, this may have been due to air storage being a noisier measurement.

2.5 CONCLUSION
Energy budget closure was obtained over a relatively flat, and homogeneous cornfield where the inclusion of all storage terms improved closure. The use of heat pulse probes to measure soil heat flux and soil heat storage appear to provide greater accuracy in these measurements and help to provide closure. For this field site, air storage was found to be negligible; however including energy storage in the biomass of the corn helped to improve closure. Of the turbulent fluxes, the latent heat flux had a greater influence on closure than the sensible heat flux. This indicates that more work should be done looking into errors associated with latent heat flux.

Further work is needed for the least squares regression and inverse matrix analysis, as the results from this study were inconclusive. Ideally, this analysis should be applied to multiple complete sets of 24-hour half-hour energy budget data that have no instances of low turbulence, which this study was unable to obtain.
3.0 CONCLUSION

3.1 Introduction

Energy budget closure has long been an issue in eddy covariance systems where typically there is an underestimation of turbulent fluxes by 10-30% (Leuning et al., 2012; Stoy et al., 2013; Wilson et al., 2002). This project aimed to collect comprehensive measurements for all terms in the energy budget equation for an agricultural field. This included the use of heat pulse probes to measure soil heat flux and soil heat storage with greater accuracy. The second part of this study was to apply least squares regression and inverse matrix analysis to 24-hours of eddy covariance data to help identify areas of error.

It is important that the issue with energy budget closure in eddy covariance systems is resolved as the data collected through eddy covariance is used to calibrate and verify environmental models. Therefore, if the eddy covariance data is incorrect then these models may be compromised.

3.2 Literature Review

The initial literature review outlined key areas where errors in the energy budget equation may occur. This included instrumentation errors such as errors in the net radiation measurements (Cobos and Baker, 2003; Kohsiek et al., 2007; Leuning et al., 2012),
neglected storage components (Emmel et al., 2013; Leuning et al., 2012; Lindroth et al., 2010), and mismatch in instrument footprints (Culf et al., 2004; Foken, 2008; Oncley et al., 2007). Turbulent structures may lead to an underestimation of turbulent fluxes through advective flux divergence and large-scale turbulent structures (Finnigan et al., 2003; Foken, 2008; Harman and Finnigan, 2010; Katul et al., 2006). If neglected or inappropriately applied, frequency response corrections may also be a source of error (Leuning et al., 2012). The literature review also outlined a few key methods for dealing with energy budget imbalance, in particular forcing closure for the use of turbulent fluxes in models (Twine et al., 2000; Wohlfahrt et al., 2009).

3.3 First Objective

A field study was conducted during the summer of 2016 growing season from DOY 198-243. Comprehensive data for all components in the energy budget equation were collected. Heat pulse probes (HPP) were used to collect distributed soil heat flux and soil heat storage measurements. The use of the HPP array to measure soil heat flux and soil heat storage improved energy budget closure accounting for ~20% of the available energy. Comparatively, when the two HFP were used to measure soil heat flux ~4% less of the available energy was accounted for. The HPP array had a greater footprint than the HFP and therefore was able to capture greater soil heterogeneity. Two methods were used to measure the air heat storage: estimating storage based on the sonic temperature and using a fine-wire thermocouple profile. Although the fine-wire thermocouple array captured ~50% more energy than the sonic temperature method, air heat storage was found to be negligible and not necessary for this field site. Although a minor term, the
inclusion of heat storage in the corn improved closure by ~2.5%. Overall, these results show that the inclusion of the storage terms are an integral part of achieving energy budget closure.

Additionally, this study also found that closure had a significant relationship with the total daily latent heat flux and not the total daily sensible heat flux. Past studies have found greater closure during dry condition, such as at arid desert sites (Heusinkveld et al., 2004; Wohlfahrt et al., 2009) or during dry periods (Twine et al., 2000). Latent heat flux measurements may be more prone to instrumental errors than sensible heat flux measurements, which are more heavily influenced by landscape characteristics (Göckede et al., 2008). More work is needed looking into the effects of latent heat flux on energy budget closure and the errors in latent heat flux measurements.

3.4 Second Objective

Both single days and composite days of 24-hour half-hour eddy covariance energy budget data were collected and formed over-determined sets of linear equations. Least squares regression and inversion matrix analysis was applied to these datasets in order to identify areas of error; however, the results from this analysis were inconclusive. Many of the results were either unreasonable or too variable. This included the soil storage term, which based on the analysis could be up to 70% overestimated. The result for the soil heat flux term was also quite variable, which did not seem reasonable due to our confidence in this measurement.


