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平地造林樹種對二氧化碳通量監測、分析之研究

**Study on CO<sub>2</sub> Flux Monitoring of the  
Tree Plantations.**



委託機關：行政院農業委員會林務局

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## 摘要

本研究運用渦度相關法(Eddy Covariance method)之理論基礎於屏東設立通量觀測塔，監測平地造林地之二氧化碳通量，希望能計算出平地造林地之碳吸存能力，並將在二氧化碳減量上之具體數據估算出來，突顯本研究在全球氣候變遷、碳稅上之重要貢獻。

樣區已進行4次每木調查，試驗地範圍內共計12種造林樹種，合計調查樣木約4,200株。試驗地一至十月的平均垂直風速，平均值為-0.057，因此可發現試驗地處於穩定狀態，符合實驗的要求，風向以東風為主，由地圖判斷屬山風。大氣一至十月平均二氧化碳濃度為387.52 ppm，每日二氧化碳濃度變化幅度平均為39.99 ppm；其二氧化碳平均通量值為0.715  $\mu\text{mol}/\text{m}^2/\text{s}$ 。從二氧化碳濃度及通量的日夜週期變化，就所得數據換算之二氧化碳固定量，平均每天每公頃林地可以從空氣中固定約27.163公斤的二氧化碳，樣區160公頃可固碳1586.32公噸，換算全造林面積，則每年約可固定2875.2公噸之二氧化碳。地表淨輻射值逐月增加，於白天日照強烈時可出現最大正值，而夜晚則出現負值，表示地表能量散失；屏東試驗站一至十月的平均可感熱通量為433.07  $\text{W}/\text{m}^2$ ，白天日照強烈時可感熱通量最大值可達977.202  $\text{W}/\text{m}^2$ ，而夜晚逆溫現象發生時可感熱通量最小值為158.759  $\text{W}/\text{m}^2$ ；潛熱通量平均值從一月份7.154  $\text{W}/\text{m}^2$  逐月增加至十月份的46.051  $\text{W}/\text{m}^2$ ，於白天日照強烈時出現最大正值，而夜晚空氣溼度較大時潛熱通量值則會出現負值。

關鍵字：全球氣候變遷、二氧化碳通量、渦度相關法、碳吸存量

## Abstract

Based on the theory of Eddy Covariance method, flux monitoring towers were established in Pingtung, in order to monitor the CO<sub>2</sub> flux of the reforestation on the plain, with the hope that we can calculate the capacity of carbon storage of the reforestation on the plain, and the realistic figures in the reduction of CO<sub>2</sub> emission thereof. We sincerely hope that this study would provide some contribution to the carbon tax involved in the global climate change.

Up to the present, 4 complete enumerations have been carried; there are 12 tree species in the experimental plots, with a total of 4,200 sample trees. From January to October of 2009, east wind is the prevailing wind direction in the experimental plots, with an average wind speed of -0.057 m/s, therefore the experimental plots are under stable conditions, which meet the requirements of this study. The CO<sub>2</sub> Concentrations of each month in the experimental plots increase during night time, and reach the maximum concentration around 5 AM, and decrease gradually during day-time and reach the minimum concentration around noon-time or right after it. The average atmospheric CO<sub>2</sub> Concentration of 387.52 ppm, and the daily variation of CO<sub>2</sub> Concentration of 39.99 ppm. the average CO<sub>2</sub> flux is 0.715  $\mu\text{mol}/\text{m}^2/\text{s}$ , and the average monthly CO<sub>2</sub> flux increase from January to October of 2009. According to the CO<sub>2</sub> Concentration and the day and night cyclic variation in CO<sub>2</sub> flux, we can calculate the carbon storage capacity of forest, on the average, each ha, of forest can absorb 27.163kg of CO<sub>2</sub> from the air daily or the total experimental plots can sequester 2875.2 metric of CO<sub>2</sub> each year. The net radiation increases from January to October of 2009. And reaches the maximum positive value during the day time with great solar intensity, and reaches negative value during night time indicating the dissipation of energy. The sensible heat flux is 433.07W/m<sup>2</sup>, and reaches the maximum value during day time with maximum solar intensity and reaches the minimum value during night time when the temperature inversion phenomenon happens. The average latent heat flux is 7.154 W/m<sup>2</sup> in January of 2009, which increases to 46.051 W/m<sup>2</sup> in October, and reaches the maximum value during day time with maximum solar intensity, and approaches negative value during night time with increased atmospheric moisture content.

Keywords: Global climate change, Carbon dioxide flux, Eddy covariance method, the amount of carbon sequestration.

# 一、前言

近年來氣候異常而變遷帶來很多災難，造成人類生存上的危機，造林減碳政策是全世界目前最重要的工作。隨著全球環境變遷課題的日益重要，建立連續且長期監測地表二氧化碳、水氣、及可感熱(sensible heat)流通量(flux)的觀測站也愈趨需要。利用渦度相關法通量測量地面層與大氣 CO<sub>2</sub> 交換已是全球性研究課題，且長期監測地表二氧化碳、水氣、及可感熱(sensible heat)流通量(flux)的觀測站也愈趨需要。這些觀測站所獲得的數據也是研究區域氣候、水文、及生態的重心。美國航空及太空總署於 1998 年決定支助建立全球性的地表二氧化碳、水氣、及熱能流通量的監測網(Baldocchi et al., 2001; Kaiser, 1998)，稱為 fluxnet。Fluxnet 主要結合數個區域性監測網，分別是位於北美及南美的 AmeriFlux 在 1996 年成立，歐洲的 CarboEuroFlux 也於 2004 年成立，在澳洲和紐西蘭有 OzFlux 監測網，而加拿大地區的監測網為 Fluxnet-Canada，非洲地區的 CarboAfrica 是在 2006 年由歐盟設立，而亞洲的 AsiaFlux 在 1999 年成立，韓國也於 2002 年起成立其觀測網 KoFlux，中國大陸的 ChinaFLUX 也於 2002 年成立，加上一些獨立觀測站，根據 fluxnet 網站公布的資料顯示，全球已超過 500 個觀測站，分布範圍從南緯 30 度至北緯 70 度，遍布五個大陸的針葉林、闊葉林、熱帶林、草地、農田、北方森林、凍原、濕地等生態系。亞洲區域監測網 AsiaFlux 主要由日本主導，已有 25 個觀測站加入，中國大陸的 ChinaFlux 有 8 個觀測站加入，而與 Fluxnet 連線的觀測站有 22 個。鑑於此課題的重要性，台灣應速建立起自己的觀測站，獲取觀測值，分析其區域特性，並加入 Fluxnet 監測網。

國內平地景觀造林政策自民國 90 年 8 月 31 日經行政院核定，民國 91 年 1 月 1 日開始執行，預定至民國 96 年 12 月 31 日總共造林 25,100 公頃。至民國 94 年底止，平地造林面積為 8,010 公頃，平地造林除了有國土保安、資源保育、景觀維護、維護生物多樣性之存續效應外，造林木可從空氣中吸收二氧化碳、改善大氣組成，降低溫室效應，正是減低二氧化碳最環保、最低成本與最有效的方

法，平地景觀造林政策是臺灣配合京都議定書，善盡地球村一份子的責任，監測評估平地造林地二氧化碳通量之變化，提昇我國友善環境的形象。

本研究運用渦度相關法(Eddy Covariance method)之理論基礎於屏東設立通量觀測塔，監測平地造林地之二氧化碳通量，希望能計算出平地造林地之碳吸存能力，並將在二氧化碳減量上之具體數據估算出來，突顯本研究在全球氣候變遷、碳稅上之重要貢獻。

## 二、材料與方法

### 1. 試驗樣區位置

本試驗觀測站設置於屏東縣新埤鄉海豐段 176 號，該區段屬台灣糖業股份有限公司屏東區處萬隆農場，合計總面積約為 290.66 ha。平地景觀造林開始於民國 91 至民國 94 年止，於萬隆農場 25 個區塊中共計栽植 14 個樹種，栽植密度每公頃 1500 株，共計栽植 435,990 株造林木，各區塊詳細栽植造林年度、造林區塊、造林面積、造林樹種詳如(附錄一)。

觀測站架設於 8 號地東北角的觀測塔，可觀測範圍約為 1 平方公里，涵蓋範圍主要為萬隆農場 3、4、8、9 號地，以及此四區塊周圍的 2、5、7、10、11 號地等五個區塊，因此觀測塔所測得的二氧化碳通量資料主要為 2、3、4、5、7、8、9、10、11 號地等九個區塊(圖 1)。於觀測塔周邊鄰近 9 個區塊，依各區塊面積大小，系統取樣 3% 設置樣區，共設置 73 個 0.05 公頃(20x25cm)樣區，樣區面積共 3.65 公頃，對個樣區進行每木調查，測量樹高、胸徑、冠幅及枝下高，以了解試驗地林木基礎狀況。

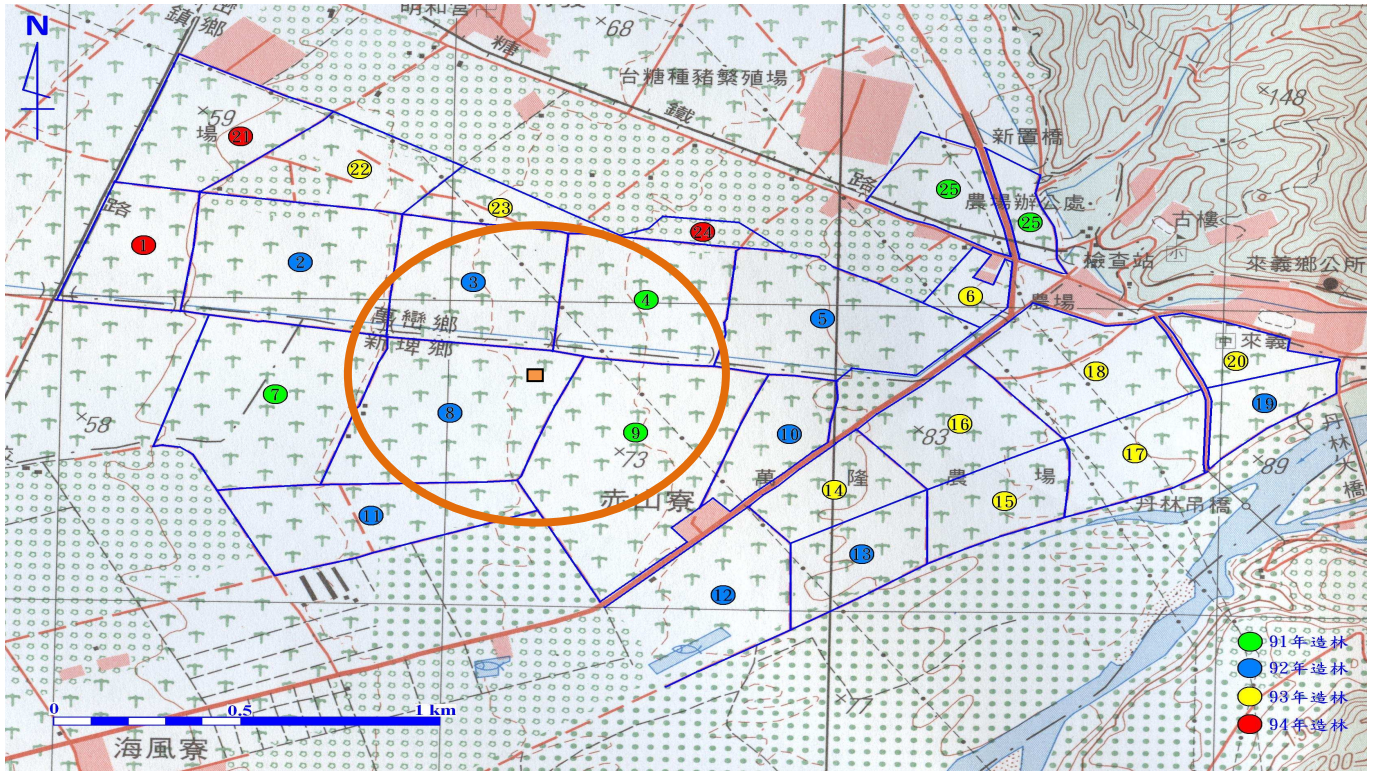


圖 1 萬隆農場 25 區塊分佈位置圖及造林年度，橘色方塊表觀測塔位置，圓框為直徑 1 公里的範圍，代表渦度相關法可觀測之範圍(背景地圖摘自經建版台灣地區二萬五千分之一地形圖)。

## 2. 研究方法

### (1) 渦度相關法(eddy covariance method)：

渦度相關法(eddy covariance method)是微氣候學的一種研究方法，而且目前是通量監測中公認最準確的方法，同時此法具有連續觀測及具有大尺度範圍之代表性的優點。國內外許多長期通量觀測站都使用渦度相關法直接量測生態系中二氧化碳、水氣、熱通量等數值(賴玫君，2007)。

渦度相關是指某物質的垂直通量，即此物質濃度與其垂直速度之共變異數(協方差，covariance)，因此二氧化碳在單位體積空間內濃度的變化率等於二氧化碳在垂直方向(z)的通量(圖 2)(宋霞等，2004)。



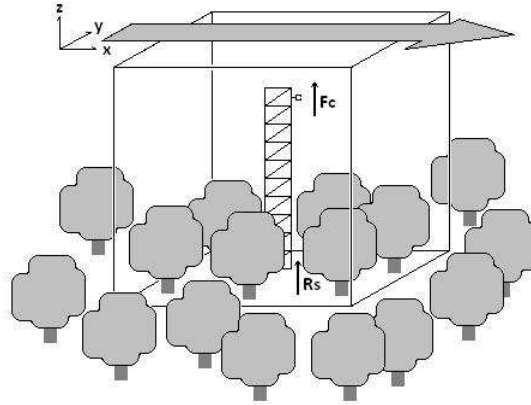


圖 2 通量觀測示意圖 (宋霞等, 2004)

大氣邊界層中之熱、水氣、動量、及其他質量的傳輸主要是由紊流主導。而渦度相關法是利用高頻率量測而得的風速與各變量之紊流訊號，以共變異數計算式求得各通量值(賴玫君, 2007)。因此二氧化碳、可感熱、潛熱通量可用下式求得(式 1、2、3)：

$$H = \rho C_p \overline{w't'} \quad (1)$$

$$LE = L_v \overline{w'q'} \quad (2)$$

$$F_{CO_2} = \overline{w'c'} \quad (3)$$

H 為可感熱通量(W/m<sup>2</sup>)；LE 為潛熱通量(W/m<sup>2</sup>)；F<sub>CO<sub>2</sub></sub> 為二氧化碳通量

$\overline{w't'}$ 、 $\overline{w'q'}$ 、 $\overline{w'c'}$  (mmole/m<sup>2</sup>s)； $\rho$  表示空氣密度(= 41.4 mol m<sup>-3</sup>)；C<sub>p</sub> 是比熱容(= 29.3 J mol<sup>-1</sup> K<sup>-1</sup>)；L<sub>v</sub> 為水的汽化熱(= 2,450 J/g)；

分別代表量測到的溫度、水氣、二氧化碳垂直紊流通量。

當觀測環境滿足以下三個大氣條件時：一、大氣觀測環境需為穩定狀態，二、水平均質的碳源、碳匯，三、大氣的下墊面為平坦地形，生態系各通量值可由三維風速計與紅外線氣體分析儀監測數據求得(宋霞等, 2003；夏禹九等, 2005)。

## (2) 渦度相關系統

本觀測站利用渦流相關系統 (eddy-covariance system) 來量測二氧化碳、水氣及熱能的通量。此系統包含：

三維音波風速計 (CAMPBELL/CSAT3 three-dimensional sonic anemometer) 及開放式紅外線氣體分析儀 (LI-COR/LI-7500 open-path infrared gas analyzer)。三維風速、氣溫、二氧化碳及水氣含量的取樣頻率為 10 Hz，每 30 分鐘計算並記錄一筆平均值資料，啟動及編輯程式如(附錄三)。

另配合各項氣象監測儀器以瞭解樣區之試驗背景資料，整合系統如下：

小型氣象感測整合套件(Vaisala WXT510)：1 套，內建風速、風向、氣溫、相對溼度、雨量等監測項目。

溫濕度計(含自然通風及防輻射裝置)HMP45C：2 組，針對冠層下方做溫度及溼度取樣取樣。

長短波輻射計(CNR1)：1 組，測量冠層上方日照輻射量。光量子計

(LI-COR/LI-190)：1 組，針對 PAR 做監測，以瞭解植被光合作用之環境資料。

紅外線溫度計(Compbell/IRTS-P)：1 組，測量冠層下方溫度。

土壤熱流量計(HFT3)：1 組、土壤溫度計(Compbell/107)：1 組、土壤水分計

(Compbell/CS616-L)：1 組，量測樣區地表條件。

各儀器架設高度如圖 3 所示：



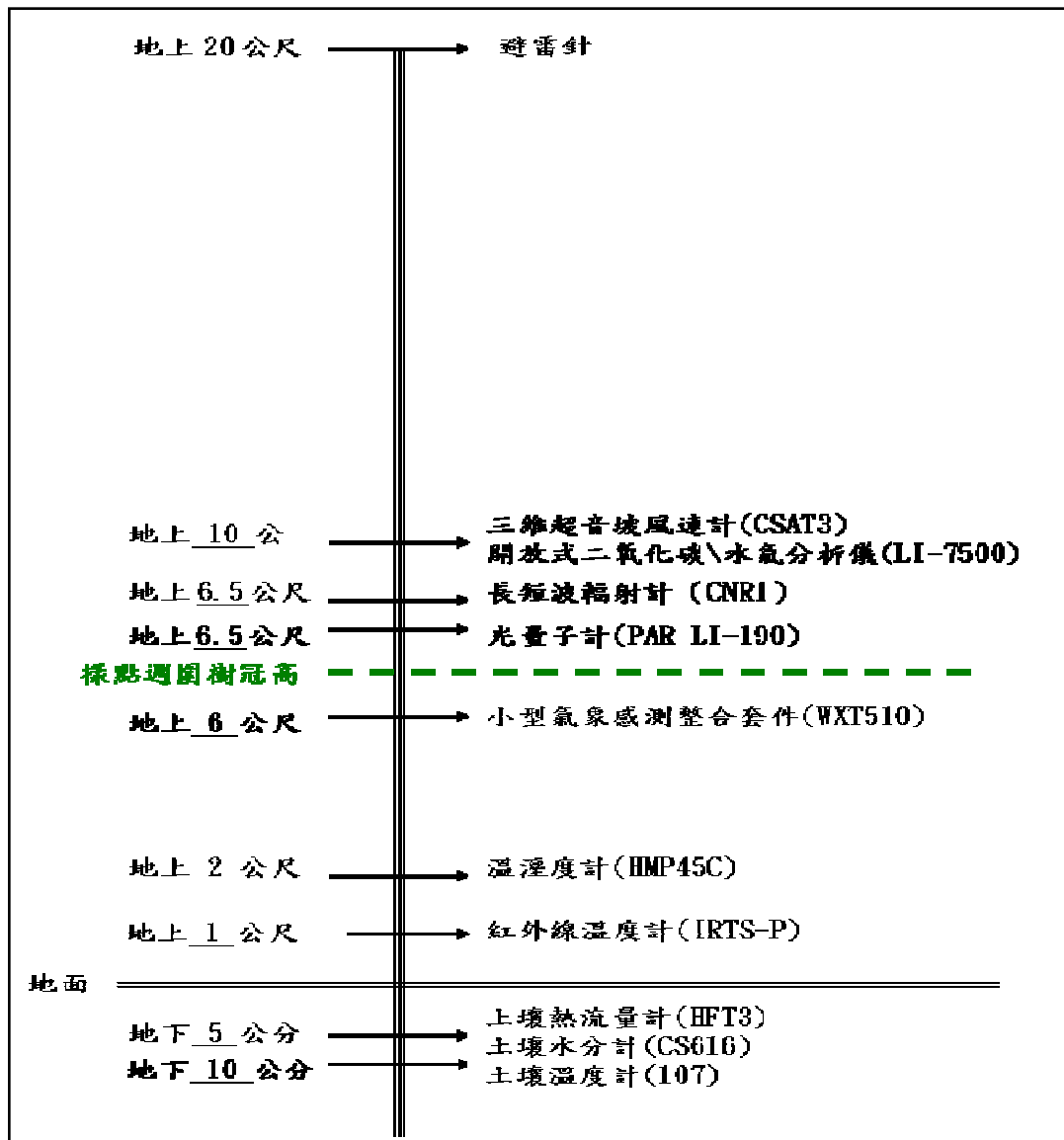


圖 3 渦度相關系統與微氣候監測儀器架設高度示意圖。

### 3. 資料處理：

渦度相關系統以頻率 10 Hz 量測生態系二氧化碳、水氣、熱通量，取得原始資料，而利用渦度相關法量測通量需符合三項基本假設：觀測地點需為地勢平坦之處、水平均勻地表存量分佈(horizontal homogeneous)、以及在某一段時間內流況為穩態(steady state)，因此大氣條件不符合的情況下，會出現錯誤的數據，需先將錯誤的量測數據除去，透過三維音波風速計所測得的資料，渦度相關系統會對資料進行初步處理，再以剩餘的原始資料，每 30 分鐘取一次平均值，代表某時間點的通量值，若是原始資料錯誤筆數過多，則需對儀器進行校調。

然而大氣的空氣密度與一些較小的組成成份(如 CO<sub>2</sub> 或水氣等)，都會影響量測到的紊流通量值，前人實驗結果發現，誤差最高甚至可達到 10%，根據表面能量守恆定律，地表淨輻射量(R<sub>n</sub>)是所有表面能量來源：部分能量提供地表熱能，稱作可感熱通量(H<sub>s</sub>)；有些則成為水氣蒸發散的能量，形成潛熱通量(LE)；其他由土壤吸收變成土壤熱通量(G)。因此可用(式 4)來判定通量值是否有誤：

$$R_n = H_s + LE + G \quad (4)$$

因此當  $H_s + LE + G \geq 1.2 * R_n$  時，該筆資料可判定為錯誤資料，又由於土壤熱通量(G)數值比潛熱通量(LE)與可感熱通量(H<sub>s</sub>)小很多，所以也可用(式 5、式 6)來判定：

$$H_s > R_n + 50 \quad (5)$$

$$LE > R_n + 50 \quad (6)$$

因此原始通量資料可用式 4、5、6 將錯誤資料去除，再以其餘資料計算平均值，若錯誤資料過多，則該筆資料（30 分鐘平均值）判定為錯誤資料。

經過資料處理，量測到的通量值可能出現資料缺失(gap)，此時可用二氧化碳通量值與地表淨輻射量兩項資料求出回歸式進行資料補遺 (gap filling)。

## 三、結果與討論

### 1. 每木調查

搭配屏東二氧化碳通量觀測站設立，於 2008 年初開始每半年進行一次每木調查，在 2008 年 1 月、7 月及 2009 年 2 月、8 月已進行四次每木調查，測量樹高、胸徑、冠幅及枝下高，以了解試驗地林木基礎狀況及林木生長情形(表 1)，合計調查樣木約 4,200 株。

試驗地範圍內共計 12 種造林樹種，於民國 91、92 年造林，造林密度 1,500

株/ha，平均樹高以苦楝最高達 5m，在今年夏季調查結果顯示桃花心木、波斯皂莢平均樹高也達 5m，從圖 4 可看出除水黃皮、土肉桂在高生長穩定增加外，大部分樹種高生長在冬季過後至夏季之間，而夏季過後至冬季之間幾乎沒有高生長。平均胸徑除土肉桂、苦楝(同時期苦楝高生長停止)穩定增加外，大部分樹種胸徑生長停滯，而桃花心木雖然在夏季至冬季間樹高生長停止，但胸徑反而在此時期大幅增加。調查初期大部分造林地尚未鬱閉，經過一年，部分造林地已鬱閉，或接近鬱閉。

表 1 試驗地林木樹種基礎資料平均值

樹種	樹高(m)				胸徑(cm)				冠輻(m)				枝下高(m)			
	08 冬	08 夏	09 冬	09 夏	08 冬	08 夏	09 冬	09 夏	08 冬	08 夏	09 冬	09 夏	08 冬	08 夏	09 冬	09 夏
土肉桂	1.54	1.75	2.32	3.23	1.03	1.76	3.42	4.4	1.18	1.23	1.49	1.79	0.47	0.5	1.49	1.79
水黃皮	2.47	2.55	2.61	2.65	3.73	4.05	4.08	4.27	1.48	1.6	1.6	1.74	1.23	1.23	1.6	1.74
台灣檫	2.33	2.74	2.73	3.23	2.51	3.13	3.12	3.57	1.78	2.04	2.02	2.27	0.98	1.03	2.02	2.27
光蠟樹	2.62	2.9	2.89	3.19	2.89	3.2	3.16	3.63	1.43	1.6	1.59	1.98	1.22	1.5	1.59	1.98
印度紫檀	4.01	4.26	4.24	4.93	5.13	6.37	6.35	6.89	2.24	2.48	2.46	2.77	1.98	1.95	2.46	2.77
波斯皂莢	4.12	4.33	4.32	5.27	5.22	5.76	5.91	6.65	1.74	1.92	2.16	2.72	1.1	1.15	2.46	2.72
茄苳	2.48	2.78	2.76	3.02	4.34	5.35	5.35	6	1.75	2.29	2.28	2.42	1.32	1.37	2.28	2.42
苦楝	4.6	5.1	5.09	5.61	5.28	5.94	6.55	7.08	2.21	2.63	2.62	2.74	2.19	2.32	2.62	2.74
桃花心木	3.58	4.18	4.18	5.05	4.22	4.51	5.64	5.92	1.23	1.34	1.34	1.55	1.88	2.14	1.34	1.55
無患子	2.47	2.79	2.79	3.16	2.29	2.83	2.83	3.42	0.88	1.35	1.35	1.06	1.38	1.37	1.35	1.06
楓香	2.27	2.45	2.45	3.19	2.66	2.76	2.76	3.59	1.1	1.39	1.39	1.75	0.91	1.04	1.39	1.75
欖仁樹	3.42	3.61	3.61	4.8	6.3	6.5	6.5	7.23	2.85	3.23	3.23	4.12	1.84	1.96	3.23	4.12

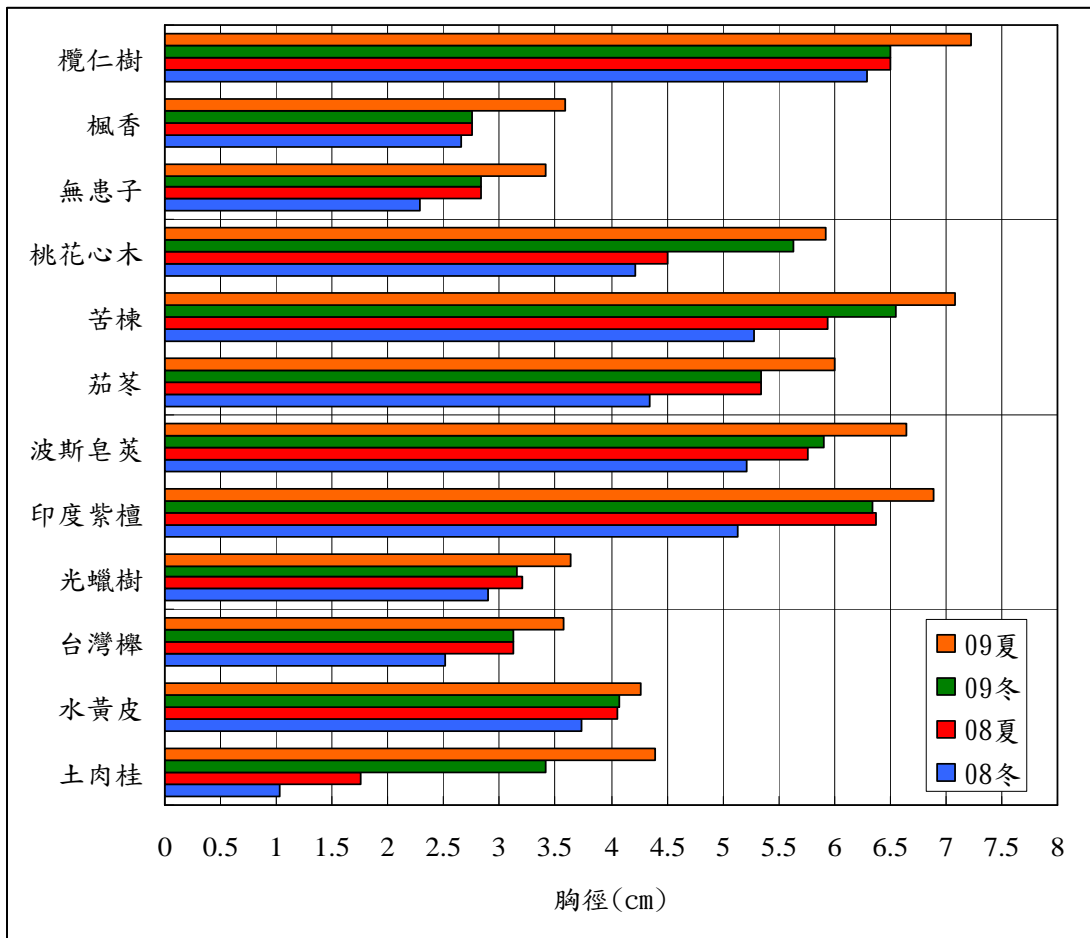
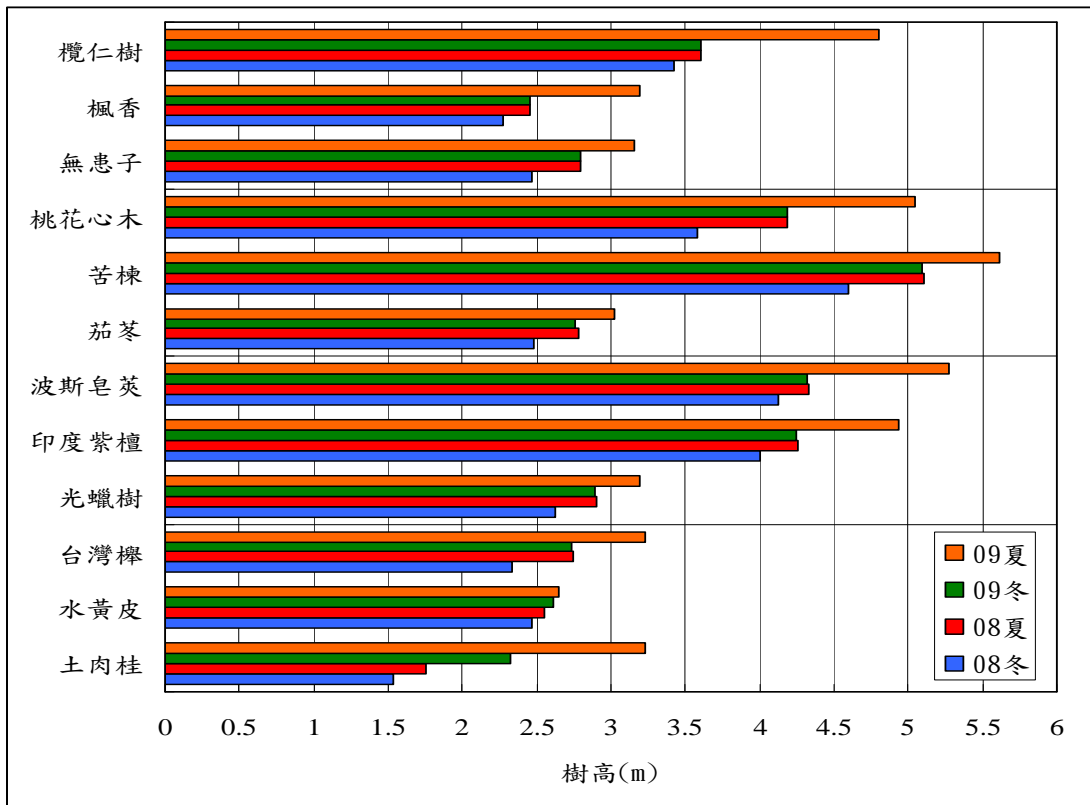


圖 4 各樹種樹高生長及胸徑生長。

屏東萬隆農場試驗地中造林木之栽植密度均為每公頃 1500 株，由觀測塔範圍內 12 種樹種的栽植面積與光合作用速率計算得光合固碳貢獻率如表 2，結果顯示在不考慮土壤呼吸及地表植被光合作用的情況下，各樹種光合固碳貢獻不同，其中印度紫檀、台灣檫及大葉桃花心木由於栽植面積大，固碳貢獻率也高，苦楝及無患子則因光合作用速率高而表現出較高的固碳貢獻率。

表 2 12 種樹種的栽植面積與光合作用速率計算得光合固碳貢獻率

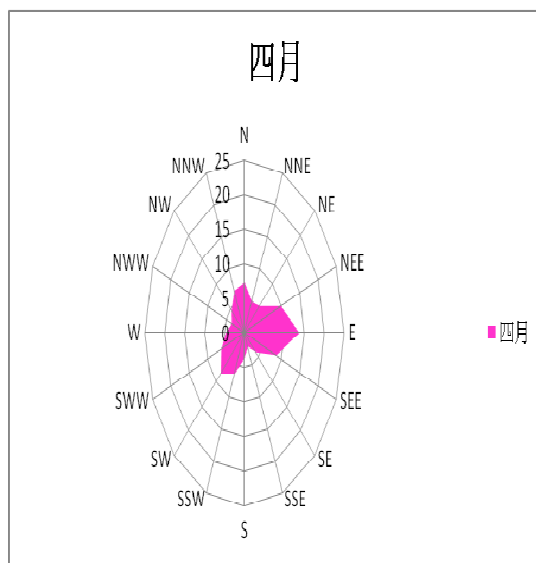
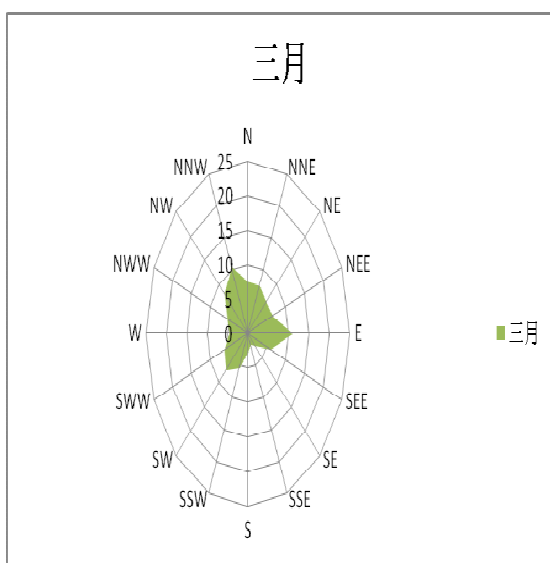
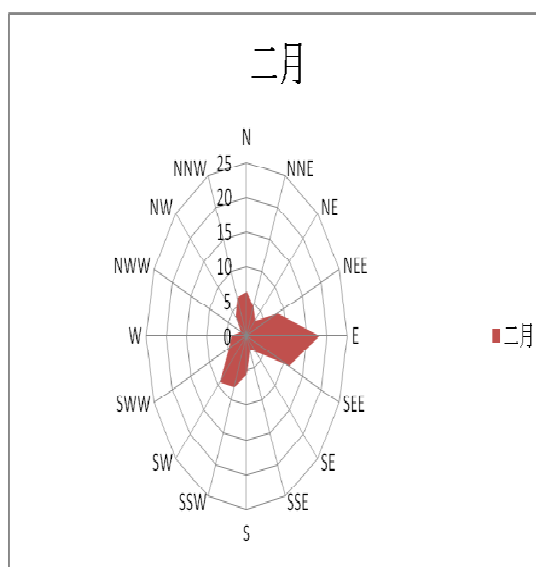
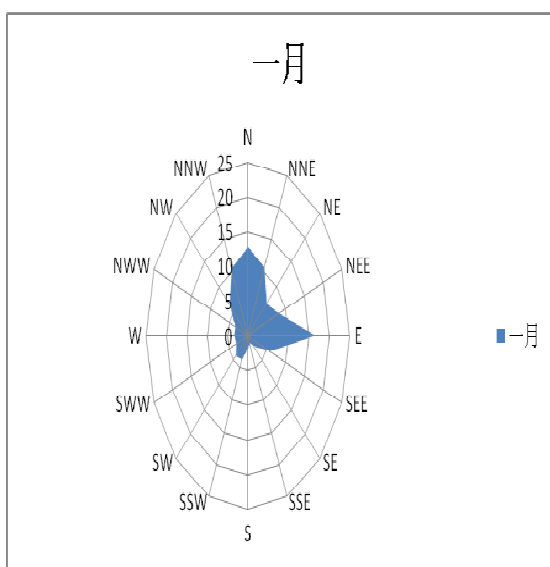
樹種	光合固碳貢獻率	面積(ha)	樹種	光合固碳貢獻率	面積(ha)
土肉桂	0.78%	0.04	茄苳	0.38%	0.02
桃花心木	11.94%	0.33	無患子	14.04%	0.18
水黃皮	1.63%	0.05	印度紫檀	19.53%	0.56
光臘樹	11.06%	0.29	楓香	0.96%	0.06
波斯皂莢	1.30%	0.09	台灣檫	13.36%	0.57
苦楝	16.23%	0.29	欖仁樹	8.79%	0.32

## 2. 平地造林地通量監測

以渦度相關法進行二氧化碳通量觀測具有非破壞性、連續觀測、及較大區域(大尺度, 100m-2km)代表性之優點, 不過需依賴穩定狀態、水平均質的碳源與碳匯、與平坦的下墊面, 將渦流三維的傳輸過程簡化為一維方向的傳輸過程, 而穩定狀態需在一段時間(通常為 30 分鐘)內之平均垂直風速為零, 而一月至十月試驗地的平均垂直風速, 數值相當小, 平均值為  $-0.057 \text{ m/s}$ , 負號表示向下, 因此可發現試驗地處於穩定狀態, 符合實驗的要求, 而平均風速為  $1.599 \text{ m/s}$ (表 3)。一月至十月風向以東風為主(圖 5), 由地圖判斷屬山風, 且穩定地在夜間發生。

表 3 觀測站風速基本資料(m/s)

時間	平均水平風速	最大水平風速	平均垂直風速
2009Jan	1.662	5.028	-0.029
2009Feb	1.824	5.123	-0.054
2009Mar	1.630	4.925	-0.044
2009Apr	1.451	4.814	-0.044
2009May	1.913	5.304	-0.073
2009Jul	1.985	5.885	-0.093
2009Aug	2.294	12.538	-0.087
2009Sep	1.952	3.300	-0.091
2009Oct	1.285	3.492	-0.057
平均值	1.599	5.041	-0.057



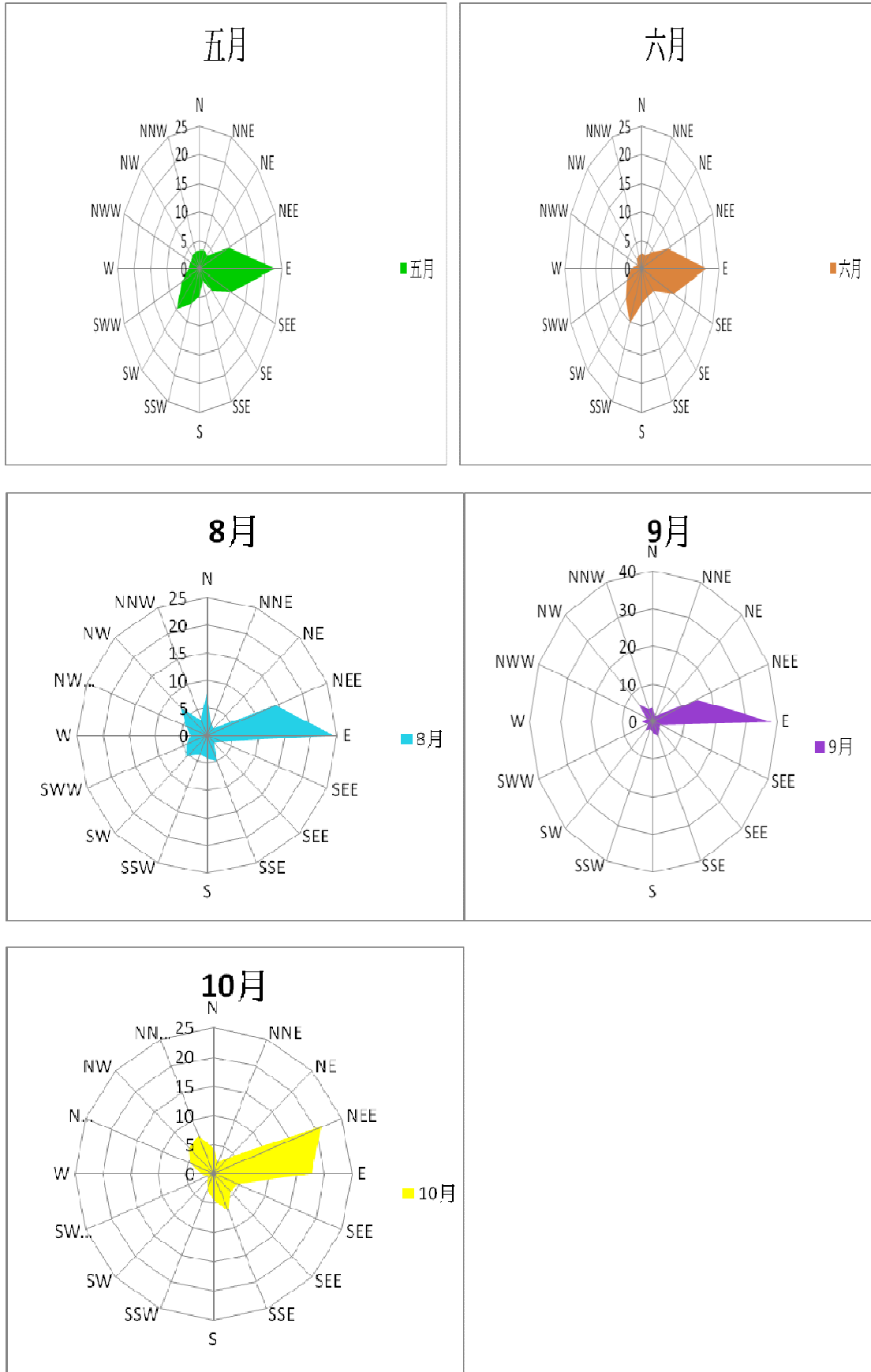


圖 5 觀測站一月至十月風向圖(%)



### 3.平地造林地之二氧化碳通量

本試驗地各月份 CO<sub>2</sub> 濃度值雖不相同，但皆在夜間上升，於清晨 5 點左右達最高濃度，並在白天逐漸下降，於中午或午後達最低濃度，由表 4 可知一至十月大氣平均二氧化碳濃度為 387.52 ppm，每日二氧化碳濃度變化幅度平均為 39.99 ppm，而每日二氧化碳濃度平均變化量也有所差異，在一至十月期間二氧化碳濃度平均變化量以一月的 29.47 ppm 最低，變化幅度逐月增加，至十月達最大值 47.18 ppm。

表 4 屏東試驗地 1 月至 10 月大氣平均二氧化碳濃度(ppm)

時間	平均值	最大值	最小值	日平均變化量
2009Jan	380.46	378.83	380.46	29.47
2009Feb	371.27	370.03	371.27	28.47
2009Mar	382.09	352.45	382.09	37.58
2009Apr	388.49	449.41	358.83	43.55
2009May	384.72	449.08	356.78	37.68
2009Jun	385.09	440.06	354.77	47.16
2009Jul	388.85	481.84	327.51	36.08
2009Aug	405.49	725.85*	349.65	49.59
2009Sep	389.47	535.73	361.24	43.16
2009Oct	399.26	586.26	348.66	47.18
平均值	387.52	—	—	39.99

從 8 月 8 日晚上開始濃度高於 500 ppm，最大值出現在 8 月 9 日凌晨 01:30，至 8 月 9 日上午才下降至 500 ppm 以下，期間試驗地處於莫拉克颱風半徑內。

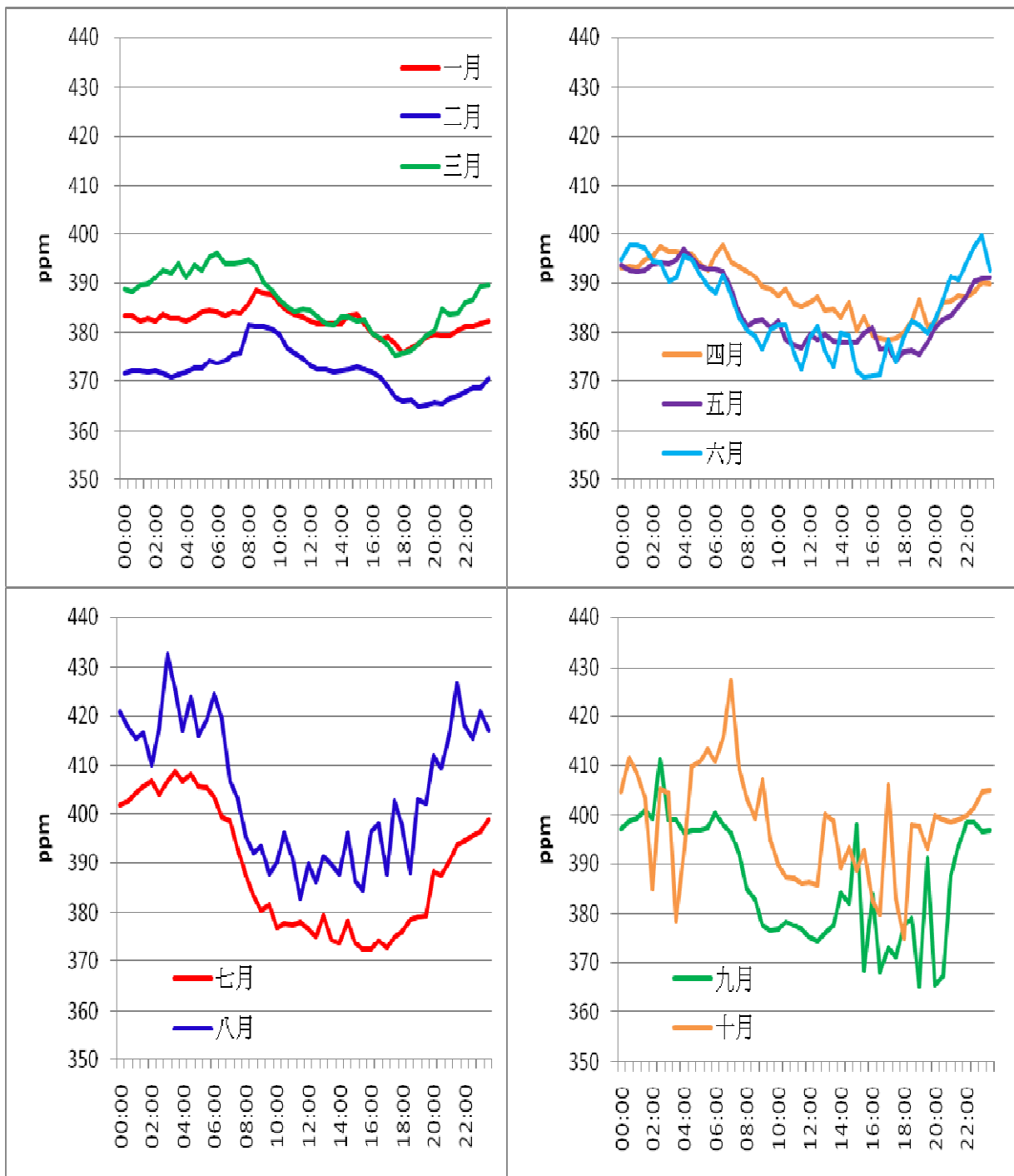


圖 6 屏東觀測站大氣二氧化碳濃度

表 5 屏東試驗地 1 月至 10 月二氧化碳通量值。

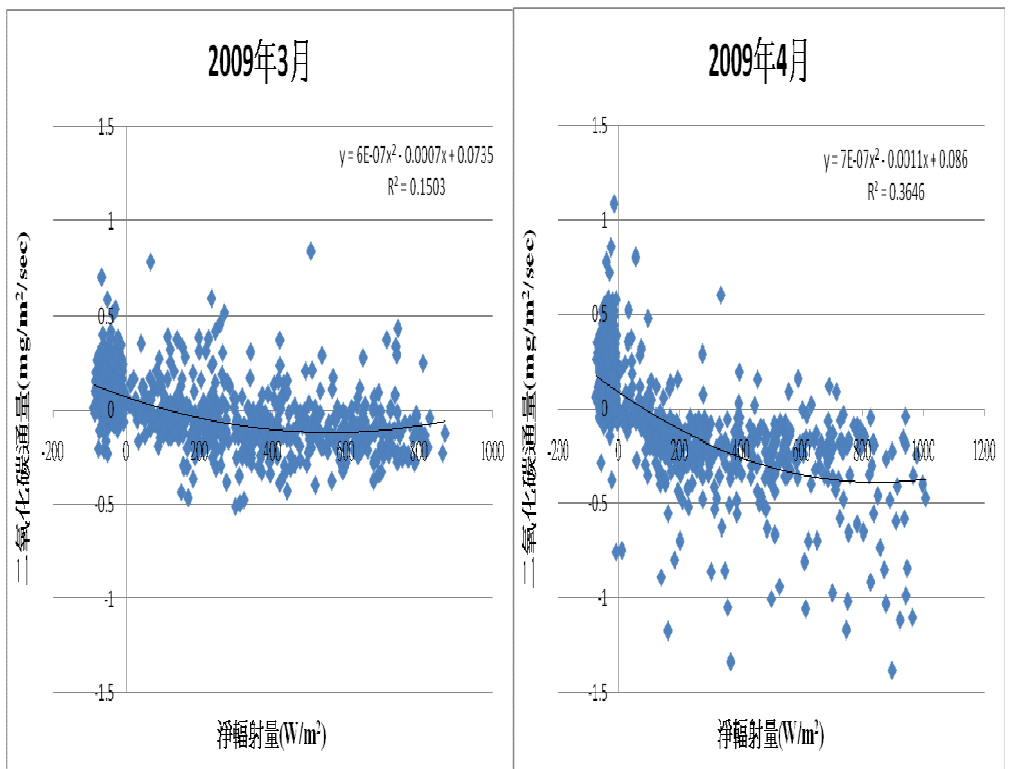
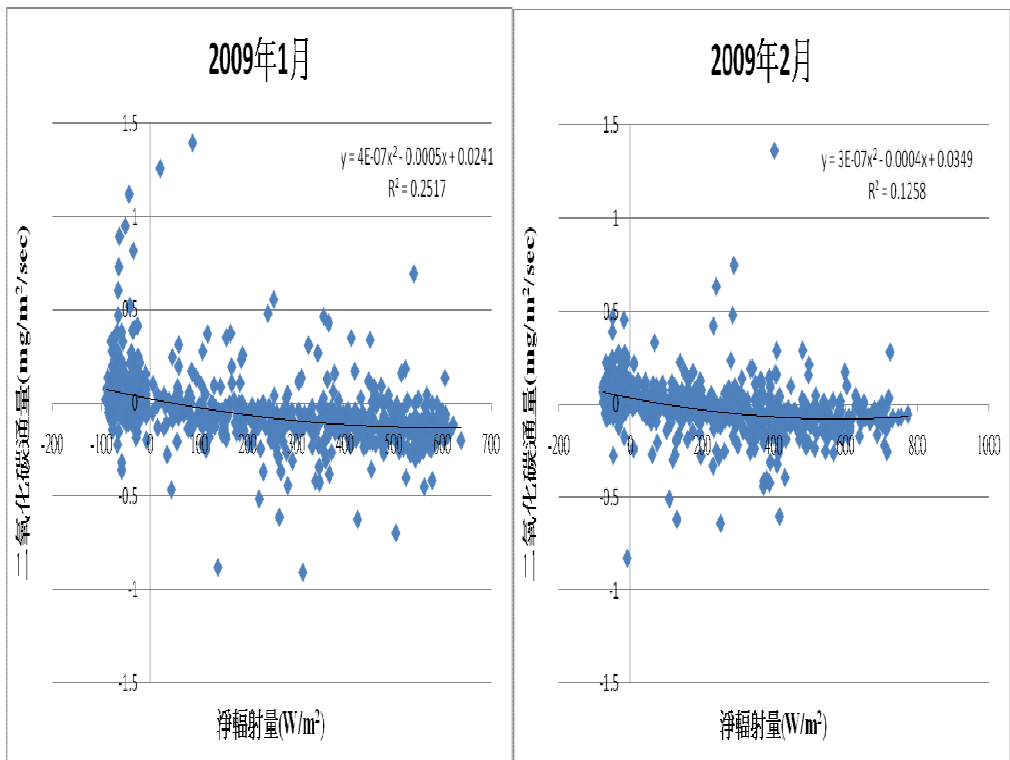
時間	平均值 ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	最小值 ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	最大值 ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	碳吸存量 ( $\text{kg}/\text{ha}/\text{day}$ )
2009Jan	0.095	-0.91	1.398	3.612
2009Feb	0.139	-25.164	11.15	5.284
2009Mar	0.374	-39.855	18.94	14.218
2009Apr	1.363	-240.881	104.297	51.816
2009May	1.036	-41.791	1.268	39.385
2009Jun	0.451	-2.542	0.691	17.145
2009Jul	0.765	-1.296	1.078	29.072
2009Aug	1.794	-2.113	1.052	68.214
2009 Sep	0.713	-23.840	50.046	27.116
2009Oct	0.415	-15.890	35.906	15.768
總平均值	0.715	-39.428	22.583	27.163

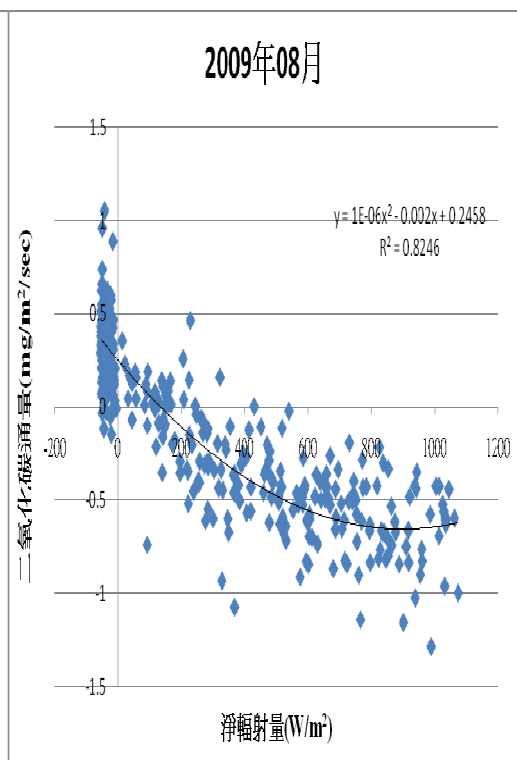
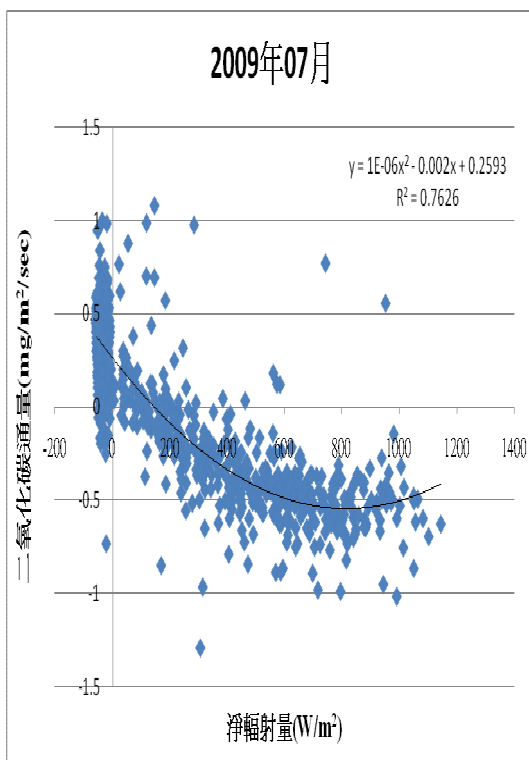
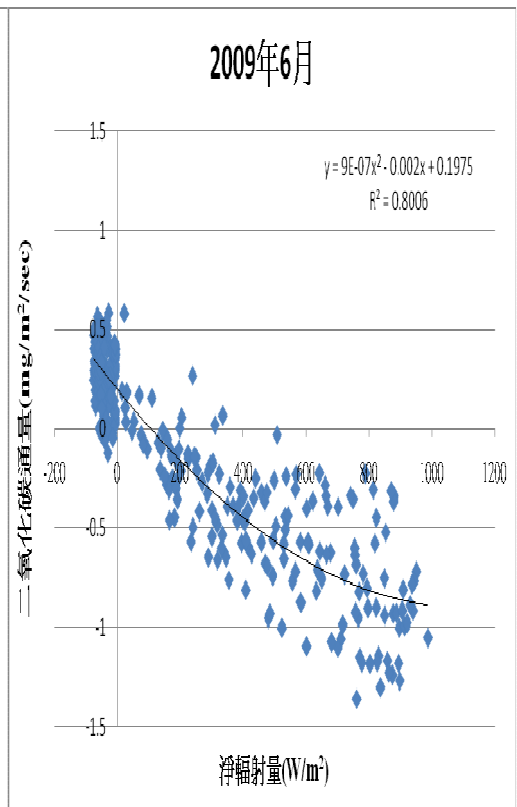
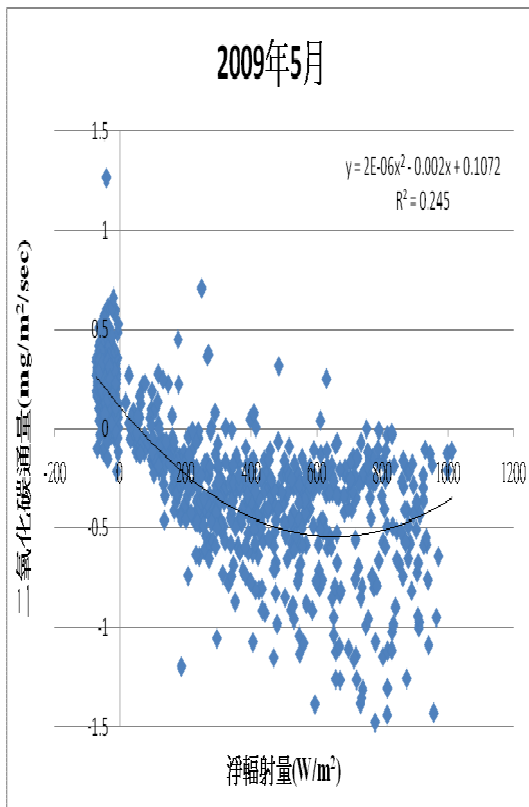
註：此處總平均值為一至十月所有二氧化碳通量及碳吸存量之平均值，而非各月份平均值之平均。

另從二氧化碳濃度及通量的日夜週期變化，就所得數據換算之二氧化碳固定量，平均每天每公頃林地可以從空氣中固定約 27.163 公斤的二氧化碳，樣區 160 公頃可固碳 1586.32 公噸，換算全造林面積，則每年約可固定 2875.2 公噸之二氧化碳。此雖僅為初估，但仍具有參考價值，預期在資料繼續累積後將日趨精準。

植物體利用太陽輻射提供之能量進行光合作用，將二氧化碳合成生長所需之葡萄糖，過程中會消耗二氧化碳，減少大氣中二氧化碳濃度。而林分二氧化碳通量由林木、地上部植被淨光合作用、土壤有機物分解、動物呼吸作用組成，由圖 7 可看出淨輻射量與二氧化碳通量之關係，隨淨輻射量增加，二氧化碳通量從正值降至負值，表示淨輻射量增加，二氧化碳從大氣進入林分中。

屏東試驗地淨輻射量約在  $-100$  至  $1200 \text{ W}/\text{m}^2$  間，最大淨輻射量逐月上升，而二氧化碳通量值 1 月至 3 月約在 0 至  $-0.2 \text{ mg}/\text{m}^2/\text{sec}$  間，4 月通量值開始上升，值約在 0 至  $-0.5 \text{ mg}/\text{m}^2/\text{sec}$  間，5 月後隨淨輻射量上升，二氧化碳通量負值明顯增加，低值可以達到約  $-1.5 \text{ mg}/\text{m}^2/\text{sec}$ ，7 月至 10 月通量值略降，低值大約在  $-1.0 \text{ mg}/\text{m}^2/\text{sec}$  左右。可以瞭解屏東試驗地在 4 月後逐漸進入生長季，有較高的二氧化碳通量值。





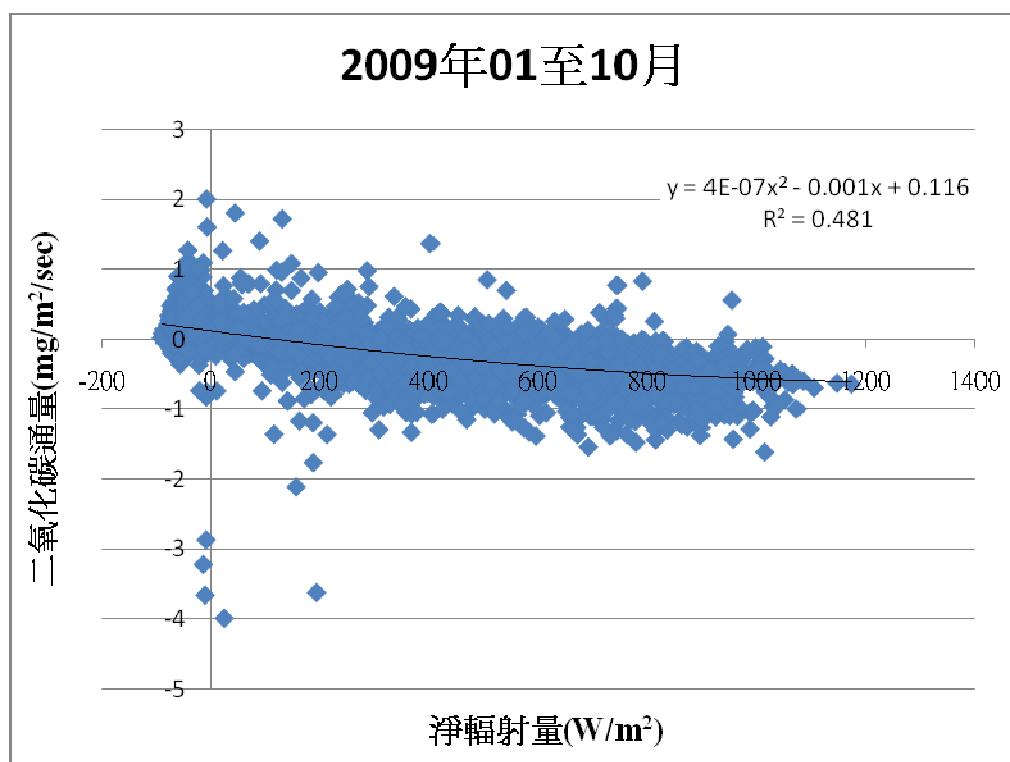
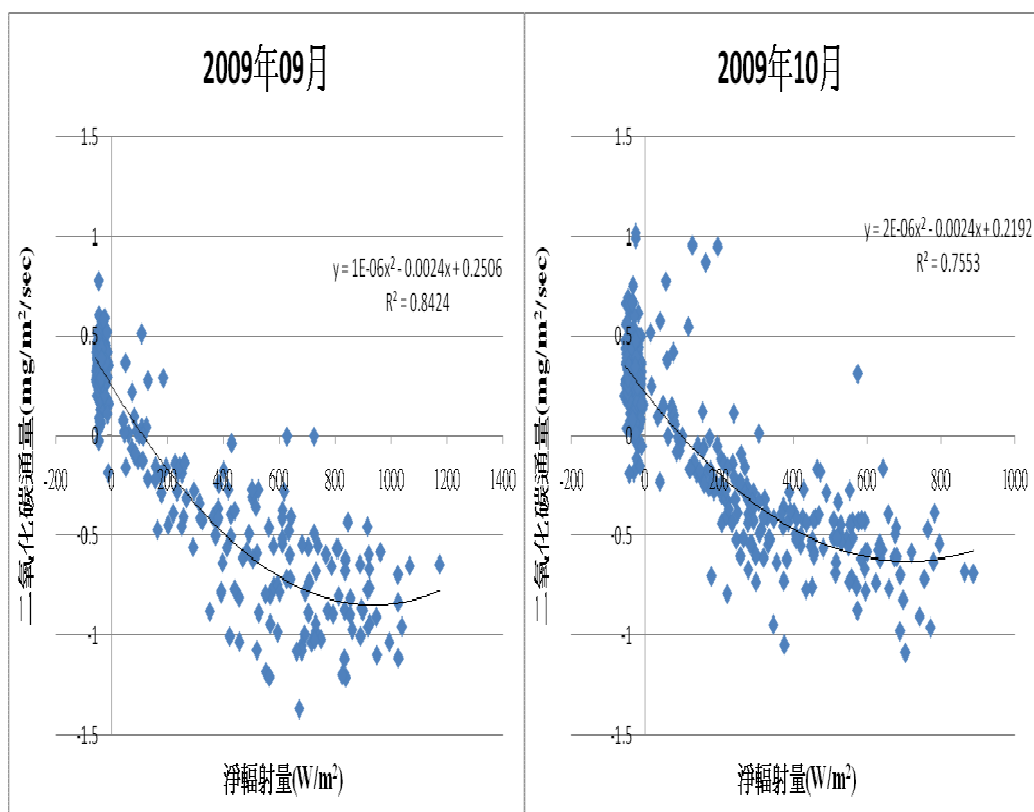


圖 7 二氧化碳通量( $F_c$ )與淨輻射量( $R_n$ )之關係

植物體透過光合作用吸收大氣中二氧化碳，而淨光合作用受許多環境因子影響，其中太陽輻射量為光合作用最主要的能量來源，而植物體周遭的溫度會影響呼吸作用，使淨光合作用值變動，植物體蒸散作用與水分利用息息相關，也影響光合作用速率，因此利用能量守恆定律，太陽輻射到達地表的淨輻射量( $R_n$ )是所有表面能量來源：部分能量提供地表熱能，稱作可感熱通量 Sensible heat flux ( $W/m^2$ ) ( $H_s$ )，會影響地表周圍的溫度；部分則成為水氣蒸發散的能量，形成潛熱通量 Latent heat flux ( $W/m^2$ ) (LE)；其他由土壤吸收變成土壤熱通量 Soil heat flux ( $W/m^2$ ) (G)。

$$R_n = H_s + LE + G$$

若等式兩側數值相差太大( $H_s + LE + G \geq 1.2 * R_n$ )，則表示儀器觀測值錯誤，該時間點之二氧化碳通量值也為錯誤數值，搭配公式可將大部分錯誤數值去除。

表 6 屏東試驗地熱通量平均值

時間	項目	平均值	最小值	最大值
2009 Jan	可感熱通量 ( $W/m^2$ )	51.612	-71.8152	414.556
	潛熱( $W/m^2$ )	7.154	-403.964	95.535
	土壤熱通量( $W/m^2$ )	6.993	-44.123	145.212
	地表淨輻射量 ( $W/m^2$ )	91.417	-90.599	638.314
2009 Feb	可感熱通量 ( $W/m^2$ )	55.591	-62.986	474.846
	潛熱( $W/m^2$ )	3.260	-259.552	322.3014
	土壤熱通量( $W/m^2$ )	6.217	-42.116	143.236
	地表淨輻射量 ( $W/m^2$ )	95.643	-76.805	773.822
2009 Mar	可感熱通量 ( $W/m^2$ )	54.530	-190.143	523.000
	潛熱( $W/m^2$ )	20.166	-313.616	954.563
	土壤熱通量( $W/m^2$ )	4.223	-43.229	140.253
	地表淨輻射量 ( $W/m^2$ )	116.942	-87.436	871.658
2009 Apr	可感熱通量 ( $W/m^2$ )	41.974	-109.675	488.125
	潛熱( $W/m^2$ )	45.065	-546.477	3269.859
	土壤熱通量( $W/m^2$ )	2.218	-41.128	136.721
	地表淨輻射量 ( $W/m^2$ )	124.749	-75.120	1007.341
2009 May	可感熱通量 ( $W/m^2$ )	43.340	-57.046	491.358
	潛熱( $W/m^2$ )	84.804	-1271.48	1195.89
	土壤熱通量( $W/m^2$ )	-1.121	-33.526	98.567
	地表淨輻射量 ( $W/m^2$ )	170.343	-73.244	1010.952



	可感熱通量 (W/m <sup>2</sup> )	18.139	-55.148	221.695
2009	潛熱(W/m <sup>2</sup> )	100.534	-496.825	994.256
Jun	土壤熱通量(W/m <sup>2</sup> )	-0.891	-21.235	88.326
	地表淨輻射量 (W/m <sup>2</sup> )	186.465	-76.277	987.075
	可感熱通量 (W/m <sup>2</sup> )	22.989	-323.852	385.435
2009	潛熱(W/m <sup>2</sup> )	97.555	-579.125	1228.792
Jul	土壤熱通量(W/m <sup>2</sup> )	28.096	24.640	32.580
	地表淨輻射量 (W/m <sup>2</sup> )	187.888	-68.3317	1146.73
	可感熱通量 (W/m <sup>2</sup> )	12.711	-283.287	195.739
2009	潛熱(W/m <sup>2</sup> )	144.401	-7595.75	8199.623
Aug	土壤熱通量(W/m <sup>2</sup> )	27.991	25.680	30.770
	地表淨輻射量 (W/m <sup>2</sup> )	147.811	-47.478	1072.976
	可感熱通量 (W/m <sup>2</sup> )	-2.892	-373.248	158.759
2009	潛熱(W/m <sup>2</sup> )	138.881	-6625.7	8159.229
Sep	土壤熱通量(W/m <sup>2</sup> )			
	地表淨輻射量 (W/m <sup>2</sup> )	173.905	-56.999	1173.613
	可感熱通量 (W/m <sup>2</sup> )	19.978	-133.055	977.202
2009	潛熱(W/m <sup>2</sup> )	46.051	-7851.26	9159.944
Oct	土壤熱通量(W/m <sup>2</sup> )	-2.641	-23.110	74.480
	地表淨輻射量 (W/m <sup>2</sup> )	121.099	-72.581	888.353

## 四、結論

- 1.目前樣區已進行4次每木調查，試驗地範圍內共計12種造林樹種，合計調查樣木約4,200株。在今年夏季調查結果除水黃皮、土肉桂在高生長穩定增加外，大部分樹種高生長在冬季過後至夏季之間，而夏季過後至冬季之間幾乎沒有高生長。平均胸徑除土肉桂、苦楝(同時期苦楝高生長停止)穩定增加外，大部分樹種胸徑生長停滯，而桃花心木雖然在夏季至冬季間樹高生長停止，但胸徑反而在此時期大幅增加。而胸徑平均一年可增加0.7cm至1.8cm，調查初期大部分造林地尚未鬱閉，經過兩年，部分造林地已鬱閉，或接近鬱閉。
2. 2009年1月至2009年10月試驗地的平均垂直風速，數值相當小，平均值為-0.057，因此可發現試驗地處於穩定狀態，符合實驗的要求，而平均風速為1.599 m/s。風向以東風為主，由地圖判斷屬山風，且穩定地在夜間發生。試驗地基本

氣象數據與預期結果十分符合，風速風向的基本條件，亦適合本套裝儀器進行監測。

3.本試驗地各月份 CO<sub>2</sub> 濃度值雖不相同，但皆在夜間上升，於清晨 5 點左右達最高濃度，並在白天逐漸下降，於中午或午後達最低濃度，由表 4 可知一至十月大氣平均二氧化碳濃度為 387.52 ppm，每日二氧化碳濃度變化幅度平均為 39.99 ppm，而每日二氧化碳濃度平均變化量也有所差異，在一至十月期間二氧化碳濃度平均變化量以一月的 29.47 ppm 最低，變化幅度逐月增加，至十月達最大值 47.16 ppm。

4.從二氧化碳濃度及通量的日夜週期變化，就所得數據換算之二氧化碳固定量，平均每天每公頃林地可以從空氣中固定約 27.163 公斤的二氧化碳，樣區 160 公頃可固碳 1586.32 公噸，換算全造林面積，則每年約可固定 2875.2 公噸之二氧化碳。此雖僅為初估，但仍具有參考價值，預期在資料繼續累積後將日趨精準。

5.分析屏東試驗地之可感熱通量、潛熱、土壤熱通量及地表淨輻射量數值。地表淨輻射值逐月增加，於白天日照強烈時可出現最大正值，而夜晚則出現負值，表示地表能量散失；屏東試驗站一至十月的平均可感熱通量為 433.07 W/m<sup>2</sup>，白天日照強烈時可感熱通量最大值可達 977.202 W/m<sup>2</sup>，而夜晚逆溫現象發生時可感熱通量最小值為 158.759 W/m<sup>2</sup>；潛熱通量平均值從一月份 7.154 W/m<sup>2</sup> 逐月增加至十月份的 46.051 W/m<sup>2</sup>，於白天日照強烈時出現最大正值，而夜晚空氣溼度較大時潛熱通量值則會出現負值(表 5)。

6.植物體光合作用速率生育地因子影響，隨季節轉換太陽輻射增強，月均溫逐月上升，而土溫也隨之漸增，相對溼度平均值則是逐月增加；基本微氣候資料顯示氣溫、土溫、空氣相對溼度有日週期性變化資料，可用於初步判斷各項儀器正常運作，並作為運算時校正的基礎。

7.樣區周圍雖然有超過 290 公頃的平地造林地，但是人為活動仍十分頻繁，畜產、農耕等活動可能會造成資料收取時的極端值出現，而產生測量與估計上的誤差。目前觀測站資料獲取率已提升至 35%，雖然與成熟觀測站相比仍偏低，隨著試驗進行與經驗累積，日後資料獲取率可望日漸上升，而本二氧化碳觀測站將逐步邁入穩定成熟。

8.試驗地造林時間最長之區塊僅有 8 年林齡，從冠幅及栽植密度評估仍屬未鬱閉林分，長期監測二氧化碳通量可進一步了解鬱閉成林過程平地造林地對二氧化碳固定量的變化。本研究監測時間尚短，但初步所得資料，仍為首次可做為台灣平地造林地二氧化碳通量之代表樣本。

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## 附錄一 觀測塔與渦度相關系統儀器照片



### 1. 二氧化碳通量觀測塔



2. 資料蒐集器(CAMPBELL-CR3000)



3. 三維超音波風速計(CAMPBELL/CSAT3)



4. 開放式二氧化碳/水氣分析儀(LI-COR/LI-7500)





5. 小型氣象感測整合套件(Vaisala WXT510)



6. 長短波輻射計(CNR1)及光量子計(LI-COR/LI-190)



7. 土壤熱流量計(HFT3)、土壤溫度計(Compbell/107)、紅外線溫度計(Compbell/IRTS-P)、土壤水分計(Compbell/CS616-L)



8. 溫濕度計(含自然通風及防輻射裝置)HMP45C



## 附錄二 三維音波風速計 (three-dimensional sonic anemometer) 及開

## 放式紅外線氣體分析儀 (LI-7500 open-path infrared gas analyzer) 細部

### 規格與啟動及編輯程式。

#### 1. 資料蒐集器規格('CR3000 Series Datalogger)

'Copyright (c) 2002, 2006 Campbell Scientific, Inc. All rights reserved.

'2 October 06

'version 2.2

'modified on 12/19/2007 by S. Ivans

'added: cnr1, 107 and cs616 sensors

' This datalogger program measures turbulence sensors at 10 or 20 Hz. The time series  
' can be saved to a card. The datalogger will also compute online turbulent fluxes  
' from the measured data. The flux table saves all the cross products that are  
' required to rotate the online fluxes into natural wind coordinates in post  
' processing as described in Kaimal and Finnigan (1994), and Tanner and Thurtell (1969).

#### 2. 與資料蒐集器連線之儀器 The following sensors are measured:

'  
'CSAT3                    three dimensional sonic anemometer  
'LI-7500                open path infrared gas analyzer (CO2 and H2O)  
'HMP45C                temperature and relative humidity probe  
'CNR1                4-way net radiometer  
'107                soil temperature probe  
'CS616                water content reflectometer (volumetric soil moisture)(one sensor)

' The sign convention for the fluxes is positive away from the surface and negative  
' towards the surface.

' The datalogger will introduce lags into the CSAT3, LI-7500, and datalogger Panel  
' Temperature data so that all measurements are aligned in time. The lags are a  
' function of the Scan Interval and are computed automatically by the program.

' The site attendant must load in several constants and calibration values. Search  
' for the text string "unique" to find the locations where unique constants and  
' calibration values are entered.

\*\*\* Unit Definitions \*\*\*

'Units	Units
'C	Celsius
'degrees	degrees (angle)
'g	grams
'J	Joules
'kg	kilograms
'kPa	kilopascals
'm	meters
'mg	milligrams
'mmol	millimoles
'mol	moles
's	seconds
'umol	micromols
'V	volts
'W	Watts

#### 3. 各項儀器接線 '\*\*\* Wiring \*\*\*

'SDM INPUT

'SDM-C1    CSAT3 SDM Data (green)

'            LI-7500 SDM Data (gray)

'SDM-C2 CSAT3 SDM Clock (white)  
' LI-7500 SDM Clock (blue)  
'SDM-C3 CSAT3 SDM Enable (brown)  
' LI-7500 SDM Enable (brown)  
'G CSAT3 SDM reference (black)  
' CSAT3 SDM shield (clear)  
' LI-7500 SDM reference (black)  
' LI-7500 SDM shield (white)

#### 'ANALOG INPUT

'1H CNR1 downwelling shortwave radiation signal (red)  
'1L CNR1 downwelling shortwave radiation signal reference (blue)  
'gnd CNR1 shield (clear)  
  
'2H CNR1 upwelling shortwave radiation signal (white)  
'2L CNR1 upwelling shortwave radiation signal reference (black)  
  
'3H CNR1 downwelling longwave radiation signal (gray)  
'3L CNR1 downwelling longwave radiation signal reference (yellow)  
  
'4H CNR1 upwelling longwave radiation signal (brown)  
'4L CNR1 upwelling longwave radiation signal reference (green)  
  
'5H HMP45C temperature signal (yellow)  
'5L HMP45C signal reference (white)  
'gnd HMP45C shield (clear)  
  
'6H HMP45C relative humidity signal (blue)  
'6L short jumper wire to 5L  
  
'7H CNR1 Pt100 (yellow)  
'7L CNR1 Pt100 (green)  
  
'8H 107 signal (red)  
'8L CS616 signal (green)  
'gnd 107 signal reference (purple)

#### 'CONTROL PORT

'C1 CS616 power control (orange)  
'G CS616 shield (clear)

#### 'VOLTAGE EXCITATION

'VX1 107 excitation (black)  
'G 107 ground (clear)

#### 'CURRENT EXCITATION

'IX1 CNR1 Pt100 (red)  
'IXR CNR1 Pt100 (blue)

#### 'POWER OUT

'12V HMP45C power (red)  
' CS616 power (red)  
'G HMP45C power reference (black)  
' CS616 signal reference (black)

#### 'POWER IN

'12V datalogger (red)  
'G datalogger (black)

#### 'EXTERNAL POWER SUPPLY

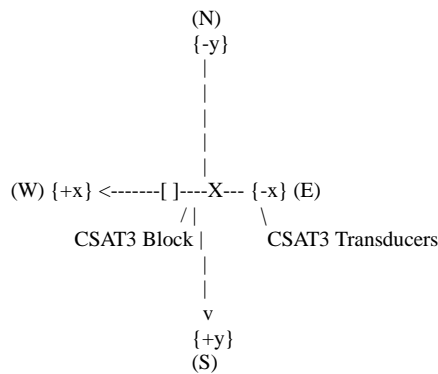
'POS CSAT3 power (red)  
' LI-7500 power (red with white)  
' datalogger (red)  
'NEG CSAT3 power reference (black)  
' CSAT3 power shield (clear)  
' LI-7500 power reference (red with black)  
' LI-7500 ground (green)  
' datalogger (black)

#### 4. 各項儀器觀測項目設定 PipeLineMode

常數項'\*\*\* Constants \*\*\*

'Measurement Rate                                    '10 Hz            20 Hz  
Const SCAN\_INTERVAL = 100                        '100 mSec            50 mSec

'Output period  
Const OUTPUT\_INTERVAL = 30                        'Online flux data output interval in minutes.  
Const NUM\_DAY\_CPU = 7                            'Number of days of data to store on the CPU.  
Const CNR1\_CAL = 150.00                        'Unique positive multiplier for CNR1 (1000/sensitivity).  
Const CSAT3\_AZIMUTH = 0                        'Unique value.  
'Compass azimuth of the -x axis. For the figure  
' below, CSAT3\_AZIMUTH = 90.  
' () -> Compass coordinate system  
' {} -> Right handed coordinate system



'The program computes the compass wind direction, using the constant  
' CSAT3\_AZIMUTH, and a CSAT3 wind direction. Good CSAT3 wind directions  
' are between -90 to 0 and 0 to 90 degrees, e.g. the wind is blowing into  
' the CSAT3 sensor head.

Const OFFSET = 16                                    'An offset delay that will be introduced to the CSAT3 and LI-7500  
data.

Const DELAY\_CSAT = 2                                'Fixed inherent lag of the CSAT3 data (two scans).

Const DELAY\_IRGA = INT (300/SCAN\_INTERVAL)       'Fixed inherent lag of the LI-7500 data (three scans at 10 Hz or six  
scans at 20 Hz).

'Determine scan buffer size, CSAT3 Execution Parameters and fixed lags for CSAT3 and LI-7500.

Const SCAN\_BUFFER\_SIZE = 60\*INT (1000/SCAN\_INTERVAL)       'Compute a 60 second scan buffer.

Const CSAT\_OPT = INT (1000/SCAN\_INTERVAL)                    'Compute CSAT3 Execution Parameter (10 or 20 Hz).

Const CSAT\_REC\_BCK = OFFSET-DELAY\_CSAT                        'Number of records back to align CSAT3 data.

Const IRGA\_REC\_BCK = OFFSET-DELAY\_IRGA                        'Number of records back to align LI-7500 data.

'Compute CPU and card storage size for the FLUX DataTables.

Const FLUX\_SIZE\_CPU = (NUM\_DAY\_CPU\*1440)/OUTPUT\_INTERVAL'Size of flux DataTable on CPU [days].

Const CP = 1004.67                                    'Estimate of heat capacity of air [J/(kg K)].

Const LV = 2440                                      'Estimate of the latent heat of vaporization [J/g].

Const SDM\_PER = 30                                    'Default SDM clock speed.

Const MU\_WPL = 29/18                                'Ratio of the molecular weight of dry air to that of water vapor.

Const R = 8.3143e-3                                'Universal gas constant [kPa m^3/(K mol) ].

Const RD = R/29                                      'Gas constant for dry air [kPa m^3/(K g)].

Const RV = R/18                                      'Gas constant for water vapor [kPa m^3/(K g)].

變數項'\*\*\* Variables \*\*\*

'Online lagged CSAT3 and LI-7500 data.

Public aligned\_data(10)

Alias aligned\_data(1) = panel\_temp

Alias aligned\_data(2) = Ux

Alias aligned\_data(3) = Uy

Alias aligned\_data(4) = Uz

Alias aligned\_data(5) = Ts

Alias aligned\_data(6) = diag\_csat

Alias aligned\_data(7) = co2

Alias aligned\_data(8) = h2o  
 Alias aligned\_data(9) = press  
 Alias aligned\_data(10) = diag\_irga  
 Units panel\_temp = C  
 Units Ux = m/s  
 Units Uy = m/s  
 Units Uz = m/s  
 Units Ts = C  
 Units diag\_csat = unitless  
 Units co2 = mg/m<sup>3</sup>  
 Units h2o = g/m<sup>3</sup>  
 Units press = kPa  
 Units diag\_irga = unitless

Public co2\_um\_m  
 Public h2o\_mm\_m  
 Units co2\_um\_m = umol/mol  
 Units h2o\_mm\_m = mmol/mol

Public diag\_bits(8) AS Boolean 'Warning flags.  
 Alias diag\_bits(1) = del\_T\_f 'Delta temperature warning flag.  
 Alias diag\_bits(2) = sig\_lck\_f 'Signal lock warning flag.  
 Alias diag\_bits(3) = amp\_h\_f 'Amplitude high warning flag.  
 Alias diag\_bits(4) = amp\_l\_f 'Amplitude low warning flag.  
 Alias diag\_bits(5) = chopper\_f 'Chopper warning flag.  
 Alias diag\_bits(6) = detector\_f 'Detector warning flag.  
 Alias diag\_bits(7) = pll\_f 'PLL warning flag.  
 Alias diag\_bits(8) = sync\_f 'Synchronization warning flag.  
 Units diag\_bits = samples  
 Public agc AS Long 'Automatic gain control.  
 Units agc = unitless

'No delay meteorological variables.

Public hmp(2) 'HMP45C temperature and relative humidity.  
 Public e\_hmp 'HMP45C vapor pressure.  
 Dim h2o\_hmp\_mean 'Mean HMP45C vapor density.  
 Dim rho\_a\_mean 'Mean air density.  
 Public batt\_volt 'Datalogger battery voltage.  
 Alias hmp(1) = t\_hmp  
 Alias hmp(2) = rh\_hmp  
 Units t\_hmp = C  
 Units rh\_hmp = percent  
 Units e\_hmp = kPa  
 Units h2o\_hmp\_mean = g/m<sup>3</sup>  
 Units rho\_a\_mean = kg/m<sup>3</sup>  
 Units batt\_volt = V

'No delay energy balance sensors.

Public Tsoil 'Soil temperature in deg C  
 Public cnr1(9) 'CNR1 Net radiometer.  
 Public cs616\_wcr 'Water content reflectometer period.  
 Public soil\_water\_T 'Volumetric soil water content with temperature correction.  
 Dim cs616\_T 'Water content reflectometer period with temperature correction.  
 Alias cnr1(1) = Rn\_cnr1  
 Alias cnr1(2) = albedo  
 Alias cnr1(3) = Rs\_downwell  
 Alias cnr1(4) = Rs\_upwell  
 Alias cnr1(5) = Rl\_downwell  
 Alias cnr1(6) = Rl\_upwell  
 Alias cnr1(7) = T\_cnr1  
 Alias cnr1(8) = Rl\_down\_meas  
 Alias cnr1(9) = Rl\_up\_meas  
 Units Tsoil = Deg C  
 Units cs616\_wcr = uSeconds  
 Units soil\_water\_T = frac\_v\_wtr  
 Units cnr1 = W/m<sup>2</sup>  
 Units albedo = unitless  
 Units T\_cnr1 = K

'Flux variables.

Dim Fc\_wpl 'Carbon dioxide flux (LI-7500), with Webb et al. term.  
 Dim LE\_wpl 'Latent heat flux (LI-7500), with Webb et al. term.  
 Dim Hs 'Sensible heat flux using sonic temperature.

Dim Hc 'Sensible heat flux computed from Hs and LE\_wpl.  
 Dim tau 'Momentum flux.  
 Dim u\_star 'Friction velocity.  
 Dim Fc\_irga 'Carbon dioxide flux (LI-7500), without Webb et al. term.  
 Dim LE\_irga 'Latent heat flux (LI-7500), without Webb et al. term.  
 Dim co2\_wpl\_LE 'Carbon dioxide flux (LI-7500), Webb et al. term due to latent heat flux.  
 Dim co2\_wpl\_H 'Carbon dioxide flux (LI-7500), Webb et al. term due to sensible heat flux.  
 Dim h2o\_wpl\_LE 'Latent heat flux (LI-7500), Webb et al. term due to latent heat flux.  
 Dim h2o\_wpl\_H 'Latent heat flux (LI-7500), Webb et al. term due to sensible heat flux.  
 Dim cov\_out(31) 'Covariances of scalars and wind, wind vector, t\_hmp\_mean, e\_mean, co2\_mean,  
 press\_mean, and Ts\_mean.  
 Units Fc\_wpl = mg/(m<sup>2</sup> s)  
 Units LE\_wpl = W/m<sup>2</sup>  
 Units Hs = W/m<sup>2</sup>  
 Units Hc = W/m<sup>2</sup>  
 Units tau = kg/(m s<sup>2</sup>)  
 Units u\_star = m/s  
 Units Fc\_irga = mg/(m<sup>2</sup> s)  
 Units LE\_irga = W/m<sup>2</sup>  
 Units co2\_wpl\_LE = mg/(m<sup>2</sup> s)  
 Units co2\_wpl\_H = mg/(m<sup>2</sup> s)  
 Units h2o\_wpl\_LE = W/m<sup>2</sup>  
 Units h2o\_wpl\_H = W/m<sup>2</sup>

'Aliases for covariances.

Alias cov\_out(1) = stdev\_Ts  
 Alias cov\_out(2) = cov\_Ts\_Ux  
 Alias cov\_out(3) = cov\_Ts\_Uy  
 Alias cov\_out(4) = cov\_Ts\_Uz  
 Alias cov\_out(5) = stdev\_Ux  
 Alias cov\_out(6) = cov\_Ux\_Uy  
 Alias cov\_out(7) = cov\_Ux\_Uz  
 Alias cov\_out(8) = stdev\_Uy  
 Alias cov\_out(9) = cov\_Uy\_Uz  
 Alias cov\_out(10) = stdev\_Uz  
 Alias cov\_out(11) = stdev\_co2  
 Alias cov\_out(12) = cov\_co2\_Ux  
 Alias cov\_out(13) = cov\_co2\_Uy  
 Alias cov\_out(14) = cov\_co2\_Uz  
 Alias cov\_out(15) = stdev\_h2o  
 Alias cov\_out(16) = cov\_h2o\_Ux  
 Alias cov\_out(17) = cov\_h2o\_Uy  
 Alias cov\_out(18) = cov\_h2o\_Uz  
 Units stdev\_Ts = C  
 Units cov\_Ts\_Ux = m C/s  
 Units cov\_Ts\_Uy = m C/s  
 Units cov\_Ts\_Uz = m C/s  
 Units stdev\_Ux = m/s  
 Units cov\_Ux\_Uy = (m/s)<sup>2</sup>  
 Units cov\_Ux\_Uz = (m/s)<sup>2</sup>  
 Units stdev\_Uy = m/s  
 Units cov\_Uy\_Uz = (m/s)<sup>2</sup>  
 Units stdev\_Uz = m/s  
 Units stdev\_co2 = mg/m<sup>3</sup>  
 Units cov\_co2\_Ux = mg/(m<sup>2</sup> s)  
 Units cov\_co2\_Uy = mg/(m<sup>2</sup> s)  
 Units cov\_co2\_Uz = mg/(m<sup>2</sup> s)  
 Units stdev\_h2o = g/m<sup>3</sup>  
 Units cov\_h2o\_Ux = g/(m<sup>2</sup> s)  
 Units cov\_h2o\_Uy = g/(m<sup>2</sup> s)  
 Units cov\_h2o\_Uz = g/(m<sup>2</sup> s)

'Wind directions and speed.

'Alias cov\_out(19) = wnd\_spd - in compass coordinate system, same as CSAT3.  
 'Alias cov\_out(20) = rslt\_wnd\_spd - in compass coordinate system, same as CSAT3.  
 Alias cov\_out(21) = wnd\_dir\_compass  
 'Alias cov\_out(22) = std\_wnd\_dir - in compass coordinate system, same as CSAT3.  
 Alias cov\_out(23) = wnd\_spd  
 Alias cov\_out(24) = rslt\_wnd\_spd  
 Alias cov\_out(25) = wnd\_dir\_csat3  
 Alias cov\_out(26) = std\_wnd\_dir  
 Alias cov\_out(27) = t\_hmp\_mean  
 Alias cov\_out(28) = e\_hmp\_mean  
 Alias cov\_out(29) = co2\_mean

Alias cov\_out(30) = press\_mean  
 Alias cov\_out(31) = Ts\_mean  
 Units wnd\_dir\_compass = degrees  
 Units wnd\_spd = m/s  
 Units rslt\_wnd\_spd = m/s  
 Units wnd\_dir\_csat3 = degrees  
 Units std\_wnd\_dir = degrees  
 Units t\_hmp\_mean = C  
 Units co2\_mean = mg/m<sup>3</sup>  
 Units press\_mean = kPa  
 Units Ts\_mean = C

'Diagnostic variables.

Dim disable\_flag\_on(4) AS Boolean 'Intermediate processing disable flags.  
 'disable\_flag\_on(1) 'TRUE when CSAT3 diagnostic warning flags are on or CSAT3 has no data.  
 'disable\_flag\_on(2) 'TRUE when LI-7500 diagnostic warning flags are on or LI-7500 failed to send data.  
 'disable\_flag\_on(3) 'TRUE when CSAT3 diagnostic warning flags are on.  
 ' Used to filter the sum of CSAT3 diagnostic warning flags.  
 'disable\_flag\_on(4) 'TRUE when LI-7500 diagnostic warning flags are on.  
 ' Used to filter the sum of LI-7500 diagnostic warning flags.  
 Dim cov\_disable\_flag AS Boolean 'TRUE when CSAT3 or LI-7500 reports bad data.  
 Dim n 'Number of samples in the online covariances.  
 Units n = samples

'No delay CSAT3 data.

Dim wind\_raw(5)  
 Alias wind\_raw(1) = Ux\_raw  
 Alias wind\_raw(2) = Uy\_raw  
 Alias wind\_raw(3) = Uz\_raw  
 Alias wind\_raw(4) = Ts\_raw  
 Alias wind\_raw(5) = diag\_csat\_raw  
 Units wind\_raw = m/s  
 Units Ts\_raw = C  
 Units diag\_csat\_raw = unitless

'No delay LI-7500 data.

Dim irga\_raw(4)  
 Alias irga\_raw(1) = co2\_raw  
 Alias irga\_raw(2) = h2o\_raw  
 Alias irga\_raw(3) = press\_raw  
 Alias irga\_raw(4) = diag\_irga\_raw  
 Units co2\_raw = umol/m<sup>3</sup>  
 Units h2o\_raw = mmol/m<sup>3</sup>  
 Units press\_raw = kPa  
 Units diag\_irga\_raw = unitless

'No delay analog measurements.

Dim panel\_temp\_raw  
 Units panel\_temp\_raw = C

'Working variables.

Dim cov\_array(3,4) 'Arrays used to hold the input data for the covariance instructions.  
 Dim co2\_mm\_m3 'Carbon dioxide concentration [mmol/m<sup>3</sup>], used to compute umol/mol concentration.  
 Dim h2o\_mm\_m3 'Water vapor concentration [mmol/m<sup>3</sup>], used to compute vapor pressure and mmol/mol concentration.  
 Dim sigma\_wpl 'Webb et al. sigma = density of water vapor / density of dry air.  
 Dim j 'Generic counter variable.  
 Dim scan\_count AS Long 'Number scans executed.  
 Dim wind\_east 'East wind in compass coordinate system.  
 Dim wind\_north 'North wind in compass coordinate system.  
 Dim save\_ts\_flag\_on AS Boolean 'Used to synchronize the time series output to the even minute.  
 Dim dly\_data\_out(10) 'Variable used to temporarily store the lagged record.  
 Dim rho\_d\_mean 'Density of dry air used in Webb et al. term [kg / m<sup>3</sup>].  
 Dim diag\_csat\_work AS Long 'Working variable used to break out the CSAT3 diagnostic bits.  
 Dim diag\_irga\_work AS Long 'Working variable used to break out the LI-7500 diagnostic bits.  
 Dim e\_sat 'Saturation vapor pressure.

##### 5. 観測数値表格輸出設定\*\*\*\* Final Output Data Tables \*\*\*

'Online flux data.

DataTable (flux,TRUE,FLUX\_SIZE\_CPU)

DataInterval (0,OUTPUT\_INTERVAL,Min,10)

CardOut (0,-1)

Sample (1,Hs,IEEE4)

Sample (1,Fc\_wpl,IEEE4)

Sample (1,LE\_wpl,IEEE4)

Sample (1,Hc,IEEE4)

Sample (1,tau,IEEE4)

Sample (1,u\_star,IEEE4)

Sample (1,Ts\_mean,IEEE4)

Sample (4,stdev\_Ts,IEEE4)

Sample (1,co2\_mean,IEEE4)

Sample (4,stdev\_co2,IEEE4)

Average (1,h2o,IEEE4,disable\_flag\_on(2))

Sample (4,stdev\_h2o,IEEE4)

Average (1,Ux,IEEE4,disable\_flag\_on(1))

Sample (3,stdev\_Ux,IEEE4)

Average (1,Uy,IEEE4,disable\_flag\_on(1))

Sample (2,stdev\_Uy,IEEE4)

Average (1,Uz,IEEE4,disable\_flag\_on(1))

Sample (1,stdev\_Uz,IEEE4)

Sample (1,press\_mean,IEEE4)

Sample (1,t\_hmp\_mean,IEEE4)

Sample (1,h2o\_hmp\_mean,IEEE4)

Sample (1,rho\_a\_mean,IEEE4)

Sample (1,wnd\_dir\_compass,IEEE4)

Sample (1,wnd\_dir\_csat3,IEEE4)

Sample (1,wnd\_spd,IEEE4)

Sample (1,rslt\_wnd\_spd,IEEE4)

Sample (1,std\_wnd\_dir,IEEE4)

Sample (1,Fc\_irga,IEEE4)

Sample (1,LE\_irga,IEEE4)

Sample (1,co2\_wpl\_LE,IEEE4)

Sample (1,co2\_wpl\_H,IEEE4)

Sample (1,h2o\_wpl\_LE,IEEE4)

Sample (1,h2o\_wpl\_H,IEEE4)

Totalize (1,n,IEEE4,cov\_disable\_flag)

Totalize (1,n,IEEE4,NOT (disable\_flag\_on(1) OR disable\_flag\_on(3)))

FieldNames ("csat\_warnings")

Totalize (1,n,IEEE4,NOT (disable\_flag\_on(2) OR disable\_flag\_on(4)))

FieldNames ("irga\_warnings")

Totalize (1,n,IEEE4,NOT (del\_T\_f) OR NOT (disable\_flag\_on(3)))

FieldNames ("del\_T\_f\_Tot")

Totalize (1,n,IEEE4,NOT (sig\_lck\_f) OR NOT (disable\_flag\_on(3)))

FieldNames ("sig\_lck\_f\_Tot")

Totalize (1,n,IEEE4,NOT (amp\_h\_f) OR NOT (disable\_flag\_on(3)))

FieldNames ("amp\_h\_f\_Tot")

Totalize (1,n,IEEE4,NOT (amp\_l\_f) OR NOT (disable\_flag\_on(3)))

FieldNames ("amp\_l\_f\_Tot")

Totalize (1,n,IEEE4,NOT (chopper\_f) OR NOT (disable\_flag\_on(4)))

FieldNames ("chopper\_f\_Tot")

Totalize (1,n,IEEE4,NOT (detector\_f) OR NOT (disable\_flag\_on(4)))

FieldNames ("detector\_f\_Tot")

Totalize (1,n,IEEE4,NOT (pll\_f) OR NOT (disable\_flag\_on(4)))

FieldNames ("pll\_f\_Tot")

Totalize (1,n,IEEE4,NOT (sync\_f) OR NOT (disable\_flag\_on(4)))

FieldNames ("sync\_f\_Tot")

Average (1,agc,IEEE4,disable\_flag\_on(2))

Average (1,panel\_temp,IEEE4,FALSE)

Average (1,batt\_volt,IEEE4,FALSE)

Average(1,Tsoil,FP2,False)

Average (1,soil\_water\_T,IEEE4,FALSE)



```
Average (1,cs616_wcr,IEEE4,FALSE)
Average (9,Rn_cnr1,IEEE4,FALSE)
```

EndTable

'Time series data.

```
DataTable (ts_data,save_ts_flag_on,-1)
  DataInterval (0,SCAN_INTERVAL,mSec,100)
  CardOut (0,-1)

  Sample (1,Ux,IEEE4)
  Sample (1,Uy,IEEE4)
  Sample (1,Uz,IEEE4)
  Sample (1,Ts,IEEE4)
  Sample (1,co2,IEEE4)
  Sample (1,h2o,IEEE4)
  Sample (1,press,IEEE4)
  Sample (1,diag_csat,IEEE4)
  Sample (1,t_hmp,IEEE4)
  Sample (1,e_hmp,IEEE4)
```

EndTable

\*\*\* Working Data Tables \*\*\*

'Reorder the data and prepare to lag all the data.

```
DataTable (dly_data,TRUE,OFFSET)
  Sample (1,panel_temp_raw,IEEE4)
  Sample (1,Ux_raw,IEEE4)
  Sample (1,Uy_raw,IEEE4)
  Sample (1,Uz_raw,IEEE4)
  Sample (1,Ts_raw,IEEE4)
  Sample (1,diag_csat_raw,IEEE4)
  Sample (1,co2_raw,IEEE4)
  Sample (1,h2o_raw,IEEE4)
  Sample (1,press_raw,IEEE4)
  Sample (1,diag_irga_raw,IEEE4)
```

EndTable

'Compute the flux covariances and the other cross products required to rotate the data  
'into natural wind coordinates. This data is output every OUTPUT\_INTERVAL minutes.

```
DataTable (comp_cov,TRUE,1)
  DataInterval (0,OUTPUT_INTERVAL,Min,1)

  'Compute covariances from CSAT3 data.
  Covariance (4,cov_array(1,1),IEEE4,disable_flag_on(1),10)
  'Compute covariance of CO2 against CSAT3 wind data.
  Covariance (4,cov_array(2,1),IEEE4,cov_disable_flag,4)
  'Compute covariance of H2O against CSAT3 wind data.
  Covariance (4,cov_array(3,1),IEEE4,cov_disable_flag,4)
  WindVector (1,wind_east,wind_north,IEEE4,disable_flag_on(1),0,1,2)
  WindVector (1,Uy,Ux,IEEE4,disable_flag_on(1),0,1,2)
  Average (1,t_hmp,IEEE4,FALSE)
  Average (1,e_hmp,IEEE4,FALSE)
  Average (1,co2,IEEE4,disable_flag_on(2))
  Average (1,press,IEEE4,disable_flag_on(2))
  Average (1,Ts,IEEE4,disable_flag_on(1))
```

EndTable

6. 觀測儀器使用程式'\*\*\* Program \*\*\*

```
BeginProg
  n = 1
```

```
'Set all CSAT3 variables to NaN.
Move (Ux_raw,5,NaN,1)
```

```
'Set all LI-7500 variables to NaN.
Move (co2_raw,4,NaN,1)
```

```
'Set the CS616 variables to NaN.
```

```

Move (cs616_wcr,1,NaN,1)
'Set the SDM clock speed.
SDMSpeed (SDM_PER)

Scan (SCAN_INTERVAL,mSec,SCAN_BUFFER_SIZE,0)
'Datalogger panel temperature.
PanelTemp (panel_temp_raw,250)

'Get CSAT3 wind and sonic temperature data.
CSAT3 (Ux_raw,1,3,91,CSAT_OPT)

'Get LI-7500 data.
CS7500 (co2_raw,1,7,6)

'Measure the HMP45C temperature and fraction humidity.
VoltDiff (t_hmp,2,mV1000,5,TRUE,200,250,0.1,0)

'Measure battery voltage.
Battery (batt_volt)

'Find the engineering units for the HMP45C temperature and humidity.
t_hmp = t_hmp-40

'Find the HMP45C vapor pressure (kPa).
VaporPressure (e_hmp,t_hmp,rh_hmp)

'107 Temperature Probe measurement T107_C:
BrHalf(Tsoil,1,mV20,15,1,1,4000,True,0,60Hz,800,0)
Tsoil=-53.4601+(90.807*Tsoil)+(-83.257*Tsoil^2)+(52.283*Tsoil^3)+(-16.723*Tsoil^4)+(2.211*Tsoil^5)

Measure CNR1 Net Radiometer.
VoltDiff (Rs_downwell,2,mV20C,1,TRUE,200,250,CNR1_CAL,0)
VoltDiff (Rl_down_meas,2,mV20C,3,TRUE,200,250,CNR1_CAL,0)
Resistance (T_cnr1,1,mV200,7,Ix1,1,1,1675,TRUE,TRUE,200,250,1,0)
T_cnr1 = T_cnr1/100
PRT (T_cnr1,1,T_cnr1,1,273.15)

'Compute net radiation, albedo, downwelling and upwelling longwave radiation.
Rn_cnr1 = Rs_downwell-Rs_upwell+Rl_down_meas-Rl_up_meas
albedo = Rs_upwell/Rs_downwell
Rl_downwell = Rl_down_meas+(5.67e-8*T_cnr1*T_cnr1*T_cnr1*T_cnr1)
Rl_upwell = Rl_up_meas+(5.67e-8*T_cnr1*T_cnr1*T_cnr1*T_cnr1)

'Measure the CS616 soil water content probes.
CS616 (cs616_wcr,1,16,1,2,1,0)

'Apply temperature correction to CS616 period and find volumetric water content.

If ( (10 <= Tsoil) AND (Tsoil <= 40) ) Then
    cs616_T = cs616_wcr+(20-Tsoil)*(0.526+cs616_wcr*(-0.052+cs616_wcr*0.00136))
Else
    cs616_T = cs616_wcr
EndIf
soil_water_T = -0.0663+cs616_T*(-0.0063+cs616_T*0.0007)

'Lag the CSAT3 and LI-7500 measurements.
CallTable dly_data

If ( scan_count >= OFFSET ) Then
'Load in the analog data that has been lagged by OFFSET scans.
GetRecord (dly_data_out(1),dly_data,OFFSET)
Move (panel_temp,1,dly_data_out(1),1) 'panel_temp

'Load in CSAT3 data that has been lagged by CSAT_REC_BCK scans.
GetRecord (dly_data_out(1),dly_data,CSAT_REC_BCK)
Move (Ux,5,dly_data_out(2),5) 'Ux, Uy, Uz, Ts, diag_csat

'Load in the LI-7500 data that has been lagged by IRGA_REC_BCK scans.
GetRecord (dly_data_out(1),dly_data,IRGA_REC_BCK)
Move (co2,4,dly_data_out(7),4) 'co2, h2o, press, diag_irga

'Copy and convert CSAT3 for compass wind vector computation.
wind_east = -1*Uy

```

wind\_north = Ux

'Save the molar density to compute molar concentration.  
co2\_mm\_m3 = co2  
h2o\_mm\_m3 = h2o

'Compute the molar concentration of CO2 and H2O.  
co2\_um\_m = co2\_mm\_m3\*R\*(t\_hmp+273.15)/press\*1000  
h2o\_mm\_m = h2o\_mm\_m3\*R\*(t\_hmp+273.15)/press

'Convert LI-7500 data from molar density [mmol/m^3] to mass density.  
' 44 [g/mol] - molecular weight of carbon dioxide  
' 0.018 [g/mmol] - molecular weight of water vapor  
If ( NOT (co2 = -99999) ) Then ( co2 = co2\*44 )  
h2o = h2o\*0.018

'Define 61502 as NaN.  
If ( diag\_csat = NaN ) Then ( diag\_csat = 61502 )

'Break up the four CSAT3 warning flags into four separate bits.  
diag\_csat\_work = diag\_csat  
del\_T\_f = diag\_csat\_work AND &h8000  
sig\_lck\_f = diag\_csat\_work AND &h4000  
amp\_h\_f = diag\_csat\_work AND &h2000  
amp\_l\_f = diag\_csat\_work AND &h1000

'Turn on the intermediate processing disable flag when any CSAT3 warning flag is  
' high, including the special cases NaN (61502), a Lost Trigger (61440), No Data  
' (61503), an SDM error (61441), or wrong CSAT3 embedded code (61442).  
disable\_flag\_on(1) = diag\_csat\_work AND &hf000

'Turn on only when CSAT3 diagnostic warning flags are set.  
disable\_flag\_on(3) = ( disable\_flag\_on(1) AND NOT (Ts = NaN) )

'Save the four most significant bits of the CSAT3 diagnostics, except for the  
' special cases NaN (61502), a Lost Trigger (61440), No Data (61503), an SDM  
' error (61441), or wrong CSAT3 embedded code (61442).  
If ( diag\_csat\_work < &hf000 ) Then ( diag\_csat = INT (diag\_csat\_work/&h1000) )

'Swap the LI-7500 diagnostic bit state.  
diag\_irga = diag\_irga XOR &h00f0  
diag\_irga\_work = diag\_irga

'Turn on the intermediate processing disable flag when the LI-7500 has failed to  
' send data to the datalogger via SDM. Set all flags high and rail the AGC to 94.  
If ( (co2 < -99990) OR (co2 = NaN) ) Then (diag\_irga\_work = &h00ff)

'Compute the AGC.  
agc = INT ((diag\_irga\_work AND &h000f)\*6.25+0.5)

'Break up the four LI-7500 warning flags into four separate bits.  
chopper\_f = diag\_irga\_work AND &h0080  
detector\_f = diag\_irga\_work AND &h0040  
pll\_f = diag\_irga\_work AND &h0020  
sync\_f = diag\_irga\_work AND &h0010

'Turn on the intermediate processing disable flag when any LI-7500 warning flag  
' is high, including the special cases NaN or an SDM error.  
disable\_flag\_on(2) = diag\_irga\_work AND &h00f0

'Turn on only when LI-7500 diagnostic warning flags are set.  
disable\_flag\_on(4) = ( disable\_flag\_on(2) AND NOT (diag\_irga\_work >= &h00ff) )

'Save only the four most significant bits of the LI-7500 diagnostic word.  
diag\_irga = INT (diag\_irga\_work/&h0010)

'Filter data in the covariance instruction if the CSAT3 or LI-7500 reports bad data.  
cov\_disable\_flag = disable\_flag\_on(1) OR disable\_flag\_on(2)

'Start saving the time series data on an even minute boundary.  
If ( ( NOT (save\_ts\_flag\_on) ) AND (IfTime (0,1,Min)) ) Then ( save\_ts\_flag\_on = TRUE )

```

'Save adjusted time series data.
CallTable ts_data

'Load the arrays that hold the input data for the covariance instructions.
cov_array(1,1) = Ts
Move (cov_array(1,2),3,Ux,3)
cov_array(2,1) = co2
Move (cov_array(2,2),3,Ux,3)
cov_array(3,1) = h2o
Move (cov_array(3,2),3,Ux,3)

'Compute the online covariances.
CallTable comp_cov

If ( comp_cov.Output(1,1) ) Then
  GetRecord (cov_out(1),comp_cov,1)

  'Compass wind direction will be between 0 and 360 degrees.
  wnd_dir_compass = (wnd_dir_compass+CSAT3_AZIMUTH) MOD 360

  'CSAT3 wind direction will be between 0 to 180 degrees and 0 to -180 degrees.
  If ( wnd_dir_csat3 ) > 180 Then ( wnd_dir_csat3 = wnd_dir_csat3-360 )

  h2o_hmp_mean = e_hmp_mean/((t_hmp_mean+273.15)*RV)
  rho_d_mean = (press_mean-e_hmp_mean)/((t_hmp_mean+273.15)*RD)
  rho_a_mean = (rho_d_mean+h2o_hmp_mean)/1000

  'Compute online fluxes.
  Fc_irga = cov_co2_Uz
  LE_irga = LV*cov_h2o_Uz
  Hs = rho_a_mean*CP*cov_Ts_Uz

  tau = SQR ((cov_Ux_Uz*cov_Ux_Uz)+(cov_Uy_Uz*cov_Uy_Uz))
  u_star = SQR (tau)
  tau = rho_a_mean*tau

  'Compute the standard deviation from the variance.
  stdev_Ts = SQR (stdev_Ts)
  stdev_Ux = SQR (stdev_Ux)
  stdev_Uy = SQR (stdev_Uy)
  stdev_Uz = SQR (stdev_Uz)
  stdev_co2 = SQR (stdev_co2)
  stdev_h2o = SQR (stdev_h2o)

  sigma_wpl = h2o_hmp_mean/rho_d_mean

  'LI-7500 Webb et al. term for water vapor Eq. (25).
  h2o_wpl_LE = MU_WPL*sigma_wpl*LE_irga
  h2o_wpl_H =
(1+(MU_WPL*sigma_wpl))*h2o_hmp_mean/(t_hmp_mean+273.15)*LV*cov_Ts_Uz
  LE_wpl = LE_irga+h2o_wpl_LE+h2o_wpl_H

  'Compute a sensible heat flux from Hs and LE_wpl.
  Hc =
(Hs-(rho_a_mean*CP*0.51*RD*(t_hmp_mean+273.15)*(t_hmp_mean+273.15)*LE_wpl)/(press_mean*LV))*((t_hmp_mean+273.15)/(Ts_mean+273.15))

  'LI-7500 Webb et al. term for carbon dioxide Eq. (24).
  co2_wpl_LE = MU_WPL*co2_mean/rho_d_mean*cov_h2o_Uz
  co2_wpl_H =
(1+(MU_WPL*sigma_wpl))*co2_mean/(t_hmp_mean+273.15)*Hc/(rho_a_mean*CP)
  Fc_wpl = Fc_irga+co2_wpl_LE+co2_wpl_H
EndIf

CallTable flux
Else
  scan_count = scan_count+1
EndIf
NextScan
EndProg

```

附錄三 屏東試驗地微氣候基礎資料

時間	屏東試驗地氣溫					
	2008 Nov	2008 Dec	2009 Jan	2009 Feb	2009 Mar	2009 Apr
00:00	19.21	17.14	14.67	20.32	20.55	22.00
00:30	19.15	17.01	14.53	20.19	20.45	22.08
01:00	19.02	16.76	14.37	20.08	20.25	21.95
01:30	18.96	16.50	14.28	19.97	20.08	21.80
02:00	18.80	16.37	14.13	19.78	19.99	21.58
02:30	18.80	16.29	13.97	19.70	19.89	21.43
03:00	18.56	16.19	13.90	19.77	19.82	21.34
03:30	18.43	16.15	13.82	19.57	19.71	21.25
04:00	18.38	16.05	13.71	19.80	19.63	21.38
04:30	18.30	16.07	13.64	19.69	19.62	21.34
05:00	18.24	15.96	13.49	19.62	19.55	21.29
05:30	18.16	15.96	13.30	19.36	19.37	21.01
06:00	18.13	15.93	13.32	19.30	19.19	20.93
06:30	18.11	15.73	13.29	19.26	19.22	21.15
07:00	18.44	15.84	13.31	19.38	19.70	21.79
07:30	19.26	16.50	13.92	20.02	20.55	22.65
08:00	20.21	17.66	15.11	21.03	21.51	23.5
08:30	21.23	18.95	16.29	22.13	22.55	24.24
09:00	22.26	19.99	17.86	23.20	23.40	24.95
09:30	23.05	21.23	18.95	24.11	24.13	25.48
10:00	23.72	22.17	19.91	24.9	24.74	25.94
10:30	24.34	22.97	20.70	25.54	25.22	26.37
11:00	24.67	23.58	21.49	26.03	25.73	26.85
11:30	25.00	24.12	22.07	26.55	26.10	27.08
12:00	25.21	24.49	22.58	26.73	26.45	27.19
12:30	25.39	24.80	22.89	26.96	26.49	27.41
13:00	25.39	24.93	23.13	27.02	26.41	27.26
13:30	25.45	25.07	23.15	26.88	26.40	27.04
14:00	25.23	24.87	23.29	26.85	26.27	26.82
14:30	24.86	24.76	23.15	26.53	26.22	26.63
15:00	24.48	24.57	22.97	26.43	26.09	26.50
15:30	24.30	24.17	22.71	26.01	25.86	26.31
16:00	23.95	23.51	22.31	25.71	25.57	25.96
16:30	23.49	22.94	21.79	25.28	25.25	25.68

17:00	22.90	22.09	21.09	24.85	24.85	25.57
17:30	22.09	21.11	20.25	24.39	24.40	25.04
18:00	21.58	20.35	19.35	23.81	23.84	24.55
18:30	21.20	19.84	18.54	23.23	23.23	24.08
19:00	20.85	19.28	17.94	22.81	22.81	23.74
19:30	20.52	18.87	17.27	22.42	22.38	23.50
20:00	20.20	18.57	16.78	22.19	22.09	23.29
20:30	19.97	18.31	16.36	21.97	21.89	23.10
21:00	19.74	18.01	16.05	21.64	21.62	22.89
21:30	19.67	17.81	15.66	21.51	21.45	22.78
22:00	19.56	17.56	15.43	21.33	21.27	22.58
22:30	19.51	17.43	15.24	21.10	21.08	22.41
23:00	19.39	17.28	15.07	20.88	20.89	22.26
23:30	19.17	17.07	14.84	20.65	20.69	22.06

時間	屏東試驗地氣溫					
	2009 May	2009 Jun	2009 Jul	2009 Aug	2009 Sep	2009 Oct
00:00	23.28	25.06	28.79	30.28	28.60	26.66
00:30	23.20	24.97	28.68	30.00	28.33	26.52
01:00	23.06	24.89	28.52	29.81	28.34	26.23
01:30	22.92	24.66	28.27	29.60	28.24	26.21
02:00	22.77	24.61	28.22	29.51	28.17	25.90
02:30	22.66	24.52	28.10	29.89	28.09	25.80
03:00	22.46	24.44	28.01	29.93	27.85	25.77
03:30	22.40	24.42	27.89	29.88	27.89	25.63
04:00	22.42	24.51	27.79	29.81	27.69	25.48
04:30	22.33	24.43	27.66	29.78	28.31	25.40
05:00	22.27	24.47	27.68	29.74	27.56	25.42
05:30	22.09	24.30	27.58	29.82	27.54	25.47
06:00	22.29	24.40	27.65	29.51	27.33	25.61
06:30	23.06	25.07	27.83	29.56	27.55	25.61
07:00	24.16	25.92	28.37	29.65	27.94	25.78
07:30	25.54	26.88	29.28	30.59	28.73	26.34
08:00	26.76	27.81	30.15	31.43	29.64	27.05
08:30	27.42	28.43	30.66	31.94	30.62	27.80
09:00	27.90	28.94	31.22	32.75	31.39	28.46
09:30	28.43	29.07	31.72	32.90	31.91	28.98
10:00	29.01	29.53	32.08	33.04	32.22	29.76

10:30	29.43	29.73	32.40	33.52	32.61	30.23
11:00	29.51	29.93	32.77	33.90	33.09	30.52
11:30	29.81	30.01	32.93	33.63	33.40	30.96
12:00	29.78	30.01	32.94	34.02	33.65	31.09
12:30	29.64	29.84	33.11	33.82	33.77	31.13
13:00	29.45	29.59	32.96	33.99	33.47	31.10
13:30	29.27	29.86	32.69	33.94	32.79	31.08
14:00	29.20	29.83	32.70	33.74	32.49	30.97
14:30	28.80	29.76	32.60	33.98	32.12	30.85
15:00	28.35	29.55	32.60	33.58	31.78	30.67
15:30	28.05	29.44	32.71	33.34	31.82	30.48
16:00	27.74	29.11	32.66	33.27	31.53	30.24
16:30	27.60	28.57	32.52	32.87	31.58	29.98
17:00	27.32	28.19	32.35	32.73	31.40	29.61
17:30	26.96	27.77	31.98	32.29	31.14	29.27
18:00	26.47	27.54	31.54	31.77	30.36	28.74
18:30	25.90	27.09	31.19	31.57	31.51	28.38
19:00	25.49	26.59	30.74	31.68	31.60	28.11
19:30	25.09	26.22	30.43	32.14	30.72	27.82
20:00	24.83	25.88	30.15	31.98	30.60	27.66
20:30	24.56	25.68	29.96	31.93	30.41	27.55
21:00	24.36	25.56	29.76	31.64	30.24	27.47
21:30	24.13	25.58	29.46	31.35	29.89	27.27
22:00	23.95	25.50	29.41	31.11	29.82	27.16
22:30	23.76	25.51	29.24	30.60	29.12	26.98
23:00	23.63	25.33	29.05	30.62	28.62	26.94
23:30	23.49	25.21	28.99	30.30	28.66	26.66

時間	屏東試驗地相對溼度					
	2008 Nov	2008 Dec	2009Jan	2009Feb	2009Mar	2009Apr
00:00	82.34	77.49	78.24	78.49	81.44	80.16
00:30	81.95	77.89	78.91	78.61	81.29	79.00
01:00	82.26	78.80	78.92	78.44	81.42	79.19
01:30	83.10	79.92	79.35	78.51	81.71	79.90
02:00	83.14	80.20	79.95	78.33	81.66	80.76
02:30	82.17	79.97	80.33	78.09	81.56	81.00
03:00	83.43	80.09	80.60	77.55	81.65	80.82
03:30	84.16	80.14	80.32	78.19	81.79	80.81

04:00	83.72	80.30	80.78	78.07	81.83	81.13
04:30	83.93	79.71	81.24	78.22	81.78	81.15
05:00	84.20	79.80	13.49	19.62	19.55	21.29
05:30	84.34	79.51	82.75	78.75	82.59	81.30
06:00	84.37	79.38	82.33	78.68	82.64	81.72
06:30	84.49	80.33	82.12	78.65	82.50	81.05
07:00	83.37	79.73	81.75	78.28	80.79	78.31
07:30	80.29	77.40	79.12	76.17	77.31	74.80
08:00	76.95	73.38	75.21	72.92	74.04	71.54
08:30	74.25	68.67	70.58	69.37	69.92	67.62
09:00	70.17	64.76	64.40	65.29	66.55	65.26
09:30	66.14	59.55	59.41	61.66	63.75	62.55
10:00	62.62	55.32	55.18	57.71	61.05	60.57
10:30	59.47	52.36	52.11	54.63	59.37	58.85
11:00	57.98	49.52	49.28	52.85	57.58	57.06
11:30	56.09	47.57	47.43	51.24	55.88	56.85
12:00	55.25	46.18	45.36	51.01	54.99	57.00
12:30	55.54	45.35	44.58	51.10	56.07	56.49
13:00	55.97	44.91	44.27	50.81	56.89	57.50
13:30	56.20	44.83	44.23	52.44	57.59	58.81
14:00	58.08	46.67	44.26	53.31	58.52	59.68
14:30	60.70	48.07	45.26	54.84	58.11	60.16
15:00	62.63	49.01	45.96	55.73	58.75	60.70
15:30	63.68	51.31	47.19	57.48	59.81	61.28
16:00	65.30	53.00	48.64	58.28	60.95	63.25
16:30	67.44	55.09	51.17	60.30	62.46	64.52
17:00	69.35	58.64	54.10	62.35	64.12	65.29
17:30	73.54	63.03	57.30	64.70	65.80	68.05
18:00	75.18	66.60	61.25	67.91	68.55	70.53
18:30	77.11	69.42	64.07	70.46	71.42	73.19
19:00	77.06	71.31	66.62	72.80	72.93	75.15
19:30	78.06	73.12	68.74	74.80	74.5	76.38
20:00	79.53	74.27	70.34	75.78	76.20	77.00
20:30	80.64	75.31	72.00	76.02	76.94	77.71
21:00	81.16	76.38	72.99	77.14	78.01	78.80
21:30	80.46	76.65	74.52	77.11	78.26	78.83
22:00	80.84	77.15	75.38	77.28	78.35	79.01
22:30	80.79	77.33	76.04	77.65	78.95	79.00



23:00	80.69	77.94	76.75	77.94	79.74	79.61
23:30	81.64	78.67	77.47	78.37	80.33	80.29
屏東試驗地相對溼度						
時間	2009May	2009Jun	2009 Jul	2009 Aug	2009 Sep	2009 Oct
00:00	79.81	81.88	83.71	81.17		85.80
00:30	79.31	81.62	83.59	80.97		85.30
01:00	79.11	81.46	84.18	81.67		85.65
01:30	79.36	82.12	84.29	82.10		86.01
02:00	79.17	81.83	83.77	81.47		85.90
02:30	78.92	81.77	83.58	81.27		85.66
03:00	78.91	81.69	83.33	81.00		85.52
03:30	78.70	81.60	83.48	81.97		85.54
04:00	78.97	82.03	83.65	80.57		85.68
04:30	78.60	82.34	83.85	81.33		85.61
05:00	22.27	24.47	83.15	81.40		85.41
05:30	77.75	81.73	82.75	83.60		85.69
06:00	76.68	81.50	81.99	81.80		85.55
06:30	73.77	79.68	80.01	83.27		85.57
07:00	69.77	76.67	77.49	81.23		85.78
07:30	65.56	73.09	73.21	78.97		83.75
08:00	62.12	70.17	70.15	76.83		79.84
08:30	59.05	68.05	68.84	75.30		75.86
09:00	56.94	65.47	66.33	71.87		71.47
09:30	53.99	65.18	64.89	70.13		67.43
10:00	52.38	63.90	64.12	68.63		64.96
10:30	51.00	62.64	63.14	53.90		62.50
11:00	51.14	61.66	62.28	55.75		62.03
11:30	50.84	62.16	62.63	53.50		60.40
12:00	51.82	62.90	62.88	54.10		59.02
12:30	53.72	63.43	62.05	55.35		59.47
13:00	54.65	65.37	63.74	62.25		60.30
13:30	56.12	63.91	65.55	59.90		61.63
14:00	55.91	64.23	66.30	62.80		62.80
14:30	57.00	64.68	66.48	65.50		64.49
15:00	58.94	65.00	65.32	67.85		64.65
15:30	61.09	65.88	66.15	65.50		65.98
16:00	62.51	66.39	66.38	65.80		66.93

16:30	62.60	69.16	66.91	65.65	67.97
17:00	63.60	70.79	68.29	69.90	69.24
17:30	65.45	73.19	71.63	71.05	71.30
18:00	67.63	74.62	73.94	69.65	73.29
18:30	70.29	75.97	76.33	72.75	77.17
19:00	72.48	78.56	79.13	78.65	80.06
19:30	74.69	81.01	80.51	81.20	81.65
20:00	76.19	82.58	81.96	81.80	83.03
20:30	77.25	83.16	82.78	82.30	83.32
21:00	78.03	83.74	83.42	78.60	83.58
21:30	79.07	82.86	84.53	77.80	83.44
22:00	79.81	82.45	84.11	77.25	83.98
22:30	80.12	82.05	84.09	77.55	83.83
23:00	80.02	82.18	84.31	78.35	84.39
23:30	80.13	82.14	83.97	78.80	84.70

時間	屏東試驗地土溫					
	2008 Nov	2008 Dec	2009Jan	2009Feb	2009Mar	2009Apr
00:00	23.09	22.34	21.65	25.56	25.43	27.37
00:30	23.10	22.22	21.49	25.38	25.23	27.11
01:00	22.79	22.11	21.33	25.20	25.05	26.90
01:30	22.87	22.01	21.18	25.04	24.89	26.69
02:00	22.80	21.91	21.04	24.89	24.74	26.51
02:30	22.94	21.81	20.90	24.74	24.59	26.33
03:00	23.20	21.71	20.78	24.60	24.46	26.16
03:30	22.83	21.62	20.65	24.47	24.33	26.01
04:00	22.67	21.54	20.6	24.56	24.15	25.97
04:30	22.50	21.45	20.49	24.46	24.03	25.83
05:00	22.45	21.37	20.37	24.35	23.90	25.86
05:30	22.40	21.29	20.21	24.03	23.84	25.62
06:00	22.34	21.21	20.10	23.95	23.72	25.50
06:30	22.29	21.13	19.99	23.86	23.60	25.38
07:00	22.24	21.07	19.89	23.77	23.51	25.27
07:30	22.21	21.02	19.81	23.70	23.5	25.19
08:00	22.23	21.04	19.76	23.69	23.59	25.14
08:30	22.29	21.11	19.81	23.79	23.82	25.11
09:00	22.41	21.28	19.96	24.04	24.19	25.10
09:30	22.61	21.56	20.22	24.45	24.73	25.11

10:00	22.82	21.82	20.66	24.96	25.37	25.13
10:30	23.03	22.21	21.16	25.57	26.15	25.18
11:00	23.28	22.74	21.77	26.29	26.94	25.24
11:30	23.52	23.23	22.53	27.08	27.7	25.32
12:00	23.73	23.65	23.26	27.82	28.39	25.40
12:30	23.90	24.01	23.89	28.38	28.98	25.51
13:00	24.10	24.38	24.50	28.84	29.42	25.68
13:30	24.33	24.73	25.05	29.27	29.79	25.90
14:00	24.53	25.00	25.52	29.62	30.13	26.14
14:30	24.65	25.18	25.86	29.87	30.4	26.39
15:00	24.71	25.26	26.07	30.03	30.57	26.73
15:30	24.70	25.24	26.13	30.12	30.61	27.07
16:00	24.65	25.15	26.06	30.11	30.53	27.31
16:30	24.57	24.98	25.91	30.00	30.32	27.51
17:00	24.46	24.77	25.67	29.79	30.02	27.67
17:30	24.34	24.53	25.36	29.50	29.61	27.78
18:00	24.20	24.29	24.99	29.14	29.15	27.91
18:30	24.07	24.07	24.62	28.74	28.67	28.12
19:00	23.94	23.86	24.25	28.35	28.21	28.39
19:30	23.82	23.65	23.91	27.98	27.81	28.67
20:00	23.69	23.47	23.58	27.64	27.45	28.83
20:30	23.58	23.30	23.28	27.33	27.12	28.82
21:00	23.46	23.14	23.00	27.04	26.83	28.71
21:30	23.36	22.99	22.74	26.77	26.56	28.55
22:00	23.27	22.84	22.5	26.52	26.32	28.39
22:30	23.18	22.70	22.28	26.29	26.09	28.18
23:00	23.09	22.57	22.08	26.08	25.85	27.92
23:30	23.01	22.51	21.89	25.87	25.63	27.64

時間	屏東試驗地土溫					
	2009May	2009Jun	2009 Jul	2009 Aug	2009 Sep	2009 Oct
00:00	26.31	26.22	27.65	27.12	26.89	25.84
00:30	26.18	26.10	27.54	27.03	26.71	25.74
01:00	26.05	25.99	27.45	26.93	26.70	25.65
01:30	25.93	25.88	27.35	26.84	26.61	25.56
02:00	25.80	25.77	27.26	26.75	26.52	25.48
02:30	25.68	25.65	27.17	26.68	26.44	25.40
03:00	25.56	25.55	27.09	26.60	26.26	25.32

03:30	25.44	25.46	27.01	26.53	26.28	25.25
04:00	25.51	25.54	26.94	26.47	26.08	25.18
04:30	25.41	25.45	26.86	26.40	26.06	25.11
05:00	25.31	25.37	26.79	26.34	25.93	25.04
05:30	25.02	25.11	26.72	26.28	25.93	24.97
06:00	24.93	25.05	26.66	26.23	25.80	24.90
06:30	24.88	25.00	26.61	26.18	25.75	24.84
07:00	24.88	25.01	26.61	26.19	25.75	24.80
07:30	24.96	25.08	26.67	26.31	25.92	24.81
08:00	25.13	25.20	26.81	26.52	26.02	24.87
08:30	25.37	25.40	27.02	26.76	26.21	24.99
09:00	25.61	25.63	27.22	27.11	26.47	25.19
09:30	25.89	25.86	27.42	27.64	26.88	25.43
10:00	26.27	26.15	27.65	28.19	27.26	25.65
10:30	26.61	26.65	27.91	28.66	27.52	25.88
11:00	26.98	27.03	28.21	29.01	27.85	26.11
11:30	27.26	27.41	28.58	29.28	28.21	26.37
12:00	27.55	27.70	28.84	29.47	28.59	26.64
12:30	27.81	27.92	29.02	29.64	28.88	26.90
13:00	28.13	28.15	29.19	29.94	29.16	27.14
13:30	28.48	28.57	29.33	30.24	29.34	27.47
14:00	28.77	28.85	29.44	30.26	29.40	27.84
14:30	28.95	28.96	29.51	30.13	29.62	28.11
15:00	29.01	28.98	29.53	30.02	29.68	28.26
15:30	29.00	28.97	29.58	29.84	29.60	28.27
16:00	28.97	29.00	29.62	29.65	29.48	28.22
16:30	28.98	28.97	29.66	29.45	29.31	28.08
17:00	28.98	28.83	29.77	29.23	29.06	27.89
17:30	28.88	28.66	29.79	28.96	28.83	27.68
18:00	28.69	28.45	29.66	28.85	28.66	27.47
18:30	28.46	28.22	29.44	28.65	28.44	27.27
19:00	28.20	27.98	29.20	28.46	28.24	27.08
19:30	27.94	27.75	28.97	28.27	28.05	26.91
20:00	27.72	27.54	28.75	28.11	27.87	26.75
20:30	27.51	27.36	28.56	27.97	27.71	26.61
21:00	27.32	27.19	28.38	27.84	27.56	26.49
21:30	27.14	27.03	28.23	27.71	27.43	26.36
22:00	26.97	26.89	28.09	27.58	27.31	26.25

22:30	26.81	26.75	27.96	27.46	27.19	26.14
23:00	26.66	26.60	27.84	27.34	27.00	26.03
23:30	26.51	26.45	27.73	27.22	26.98	25.92

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## 平地造林樹種對二氧化碳通量監測、分析之研究期末意見審查回覆

### (一)、林業試驗所簡研究員慶德

1. 參考文獻缺 Baldocchi et al.,2001 和 Kaiser,1998。

→已補上文獻出處

2. 英文摘要第二段 11-1239,“CO<sub>2</sub>”需調整一下；”m<sup>2</sup>”需調整為”m<sup>2</sup>“。

→已改正

### (二)、宜蘭大學森林暨自然資源學系林教授世宗

1. 以渦度方法運用於平地造林在CO<sub>2</sub> +lux估測分析為台灣首次的大尺度監測，甚至已較穩定建立database更屬不易。再分析解讀與平地造林的減碳量之連聯性。

2. 對各平地造林樹種由光合測定表現其對該區之吸碳貢獻度概念不錯。

→本研究運用渦度相關法(Eddy Covariance method)之理論基礎於屏東

設立通量觀測塔，監測平地造林地之二氧化碳通量，希望能計算出平地造林地之碳吸存能力，並將在二氧化碳減量上之具體數據估算出來，突顯本研究在全球氣候變遷、碳稅上之重要貢獻。從二氧化碳濃度及通量的日夜週期變化，就所得數據換算之二氧化碳固定量，平均每天每公頃林地可以從空氣中固定約 27.163 公斤的二氧化碳，樣區 160 公頃可固碳 1586.32 公噸，換算全造林面積，則每年約可固定 2875.2 公噸之二氧化碳。研究計畫會持續作監測建立相關資料分析與減碳量。

### (三)、中興大學森林學系顏副教授添明

1. 本計畫之觀測站設置於屏東縣新埤鄉屬於台糖公司萬隆農

場，運用渦度相關法之理論，監測平地景觀造林地之CO<sub>2</sub>通量，所得之結果可提供做為CO<sub>2</sub>吸存之參考。

2. 內容資料豐富而詳細，未來持續監測將可累積較多的資料，以分析相關資訊在時間系列上的變化，以瞭解平地造林對CO<sub>2</sub>吸存的貢獻。

➔ 二氧化碳通量監測已成為全球長期生態系研究之熱門項目，本試驗地設立於屏東台糖平地造林地，地形平坦，造林面積廣大(大於 120 公頃)適合進行長期生態系觀測，但原屬造林初期，日後研究成果應可提供國內平地造林地通量計算之參考。