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1 **Accounting for vegetation height and wind direction to correct eddy**
2 **covariance measurements of energy fluxes over hilly crop fields**

3

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13 **Key Points**

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15 Eddy covariance measurements are collected over rainfed hilly crop fields

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17 Airflow inclination depends upon upslope / downslope winds and crop height

18

19 Tilt corrections are adjusted accordingly, and improve energy balance closure

20

21

22 **Abstract:** As agricultural hilly watersheds are widespread throughout the world, there
23 is as strong need for reliable estimates of land surface fluxes, especially
24 evapotranspiration, over crop fields on hilly slopes. In order to obtain reliable estimates
25 from eddy covariance (EC) measurements in such conditions, the current study aimed at
26 proposing adequate planar fit tilt corrections that account for the combined effects of
27 topography, wind direction and vegetation height on airflow inclinations. EC
28 measurements were collected within an agricultural hilly watershed in northeastern
29 Tunisia, throughout the growth cycles of cereals, legumes and pasture. The wind had
30 two dominant directions that induced upslope and downslope winds. For upslope winds,
31 the airflows were parallel to the slopes and slightly came closer to the horizontal plane
32 when vegetation grew. For downslope winds, over fields located in the lee of the rim
33 top, the airflows were almost horizontal over bares soils and came closer to the
34 topographical slope when vegetation grew. We therefore adjusted the planar fit tilt
35 correction on EC measurements according to vegetation height and by discriminating
36 between upslope and downslope winds. This adjusted tilt correction improved the
37 energy balance closure in most cases, and the obtained energy balance closures were
38 similar to that reported in the literature for flat conditions. We conclude that EC data
39 collected within crop fields on hilly slopes can be used for monitoring land surface
40 fluxes, provided planar fit tilt corrections are applied in an appropriate manner.

41
42 **Keywords:** Eddy covariance measurements; Hilly slopes; Agricultural canopies;
43 Airflow inclination; Planar fit tilt correction; Energy balance closure

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46 **1. Introduction**

47 Knowledge of land surface momentum, mass and energy fluxes is of strong interest for
48 documenting land surface boundary conditions in meteorology [Boone et al., 2009;
49 Steeneveld et al., 2011], soil surface and subsurface moisture in hydrology [Gómez-
50 Delgado et al., 2011; Cai et al., 2014], and crop water consumption in agriculture
51 [Abedinpour et al., 2012; Zeri et al., 2013]. Among land surface fluxes, latent heat flux,
52 or evapotranspiration, is critical under sub-humid and semi-arid climates since it
53 corresponds to up to 80% of the yearly hydrological budget [Moussa et al., 2007]. Over
54 the last decades, work on observing and modeling land surface fluxes were mainly
55 focused on flat landscapes with sparse or full covering canopies [e.g., Courault et al.,
56 2005; Kalma et al., 2008; Allen et al., 2011; Wang and Dickinson, 2012; Chen et al.,
57 2013; Kool et al., 2014].

58 Agricultural hilly watersheds are common in many parts of the world [Zhang et
59 al., 2004; Mishra et al., 2008; Khlifi et al., 2010; Maeda et al., 2010]. They experience
60 agricultural intensification, because hilly topographies allow water-harvesting
61 techniques that compensate for rainfall shortage [Mekki et al., 2006; Saha et al., 2007].
62 In order to elaborate decision support systems and adaptation strategies for mitigating
63 the effects of global change, including climatic and anthropogenic forcings, there is a
64 need for reliable estimates of land surface fluxes, especially evapotranspiration, within
65 hilly crop fields.

66 Within hilly watersheds, topographical features and boundary layer conditions
67 are very different from those observed within flat and mountainous areas, because of
68 relief patterns, wind regimes and thermal stratification [Raupach and Finnigan, 1997].
69 Hill patterns and shapes influence the interception of solar radiation and the three-

70 dimensional structure of airflow in terms of pressure, direction and velocity [Raupach
71 and Finnigan, 1997]. Such influence combines with the effect of atmospheric stability
72 [Ross et al., 2004], as well as with land surface aerodynamic properties, including
73 roughness through vegetation density and height [Allen, 2006]. In addition, horizontal
74 advection may not be negligible [Poggi et al., 2008].

75 Experimentally, land surface fluxes have been measured in sloping conditions
76 by using eddy covariance (EC) systems [Finnigan, 2008], mostly over mountainous
77 areas with forests [Rannik, 1998; Geissbühler et al., 2000; Humphreys et al., 2003;
78 Turnipseed et al., 2003] or grasslands [Hammerle et al., 2007; Hiller et al., 2008]. Due
79 to experimental onerousness, the instrumental setups have usually involved single
80 devices [e.g. Hammerle et al., 2007; Hiller et al., 2008; Etzold et al., 2010; Liu et al.,
81 2012], and very rarely multiple devices that would permit the study of advection effects
82 [Feigenwinter et al., 2008; Zeri et al., 2010]. Only a few experiments were conducted
83 over hilly crop fields [Rana et al., 2007, 2011; Scott, 2010; Zitouna-Chebbi et al., 2012].

84 When using single EC devices over complex terrain, tilt correction techniques
85 are usually applied to virtually align the sonic anemometer perpendicular to the airflow
86 streamlines [Lee et al., 2004; Rebmann et al., 2012]. For hilly crop fields, Rana et al.
87 [2007, 2011] and Scott [2010] applied the planar fit tilt corrections by fitting a single
88 alignment plane over the whole time series of the considered EC dataset, thus assuming
89 that airflow inclination does not change throughout the experiment. However, Zitouna-
90 Chebbi et al. [2012] improved the accuracy of energy flux measurements over bare soils
91 by discriminating between upslope and downslope winds for planar fit tilt corrections.
92 Indeed, combined effects of wind direction and topography drove airflow inclination

93 that was parallel to the topographical slope for upslope winds and almost horizontal for
94 downslope winds.

95 For the outdoor experimental studies discussed above, the tilt corrections were
96 applied without considering any influence of vegetation canopy on airflow inclination.
97 However, several studies theoretically underlined this influence by using wind tunnel
98 experiments [Finnigan and Brunet, 1995; Poggi and Katul, 2007], large eddy
99 simulations (LES) techniques [Tamura et al., 2007; Dupont et al., 2008] and analytical
100 modeling approaches [e.g. Finnigan and Belcher, 2004; Ross and Vosper, 2005; Patton
101 and Katul, 2009; Harman and Finnigan, 2013]. Although limited to simple situations
102 (sinusoidal two-dimensional hills, neutral regime, deep forest canopies), these studies
103 permitted the identification of key drivers, and various analytical models were proposed
104 for specific airflow regimes induced by topography-driven pressure field or vegetation
105 canopy absorbing momentum [Poggi et al., 2008]. Finnigan and Belcher [2004] showed
106 that deep canopies could enhance the separation region in the lee side of a hill.

107 In the context of obtaining reliable EC measurements of daytime energy fluxes
108 over sloping crop fields, the current study aimed at identifying adequate tilt corrections
109 that account for the combined effects of topography, wind direction and vegetation
110 height on airflow inclinations. To this aim, an experiment was set up over the cycle of
111 various crops located on the two opposite rims of a hilly watershed in a semi arid
112 climate. The paper is structured as follows. Section 2 presents (1) the experiment, (2)
113 the calculations of airflow inclinations, land surface energy fluxes, and local wind-
114 oriented topography, and (3) the experimental conditions. Section 3 reports (1) the
115 temporal changes in airflow inclinations, (2) the changes in airflow inclination as driven
116 by the local topography and the vegetation height, and (3) the analysis of the tilt

117 corrections of flux measurements and the energy balance closure. Section 4 and 5
118 discuss the main outcomes and future directions for study.

119 **2. Materials and methods**

120 **2.1. Experimental site**

121 The experiment was set within the agricultural Kamech watershed, located in the Cap
122 Bon peninsula in northeastern Tunisia (36°52'40" N, 10°52'40" E). A description of the
123 Kamech watershed can be found in Mekki et al. [2006]. This watershed belongs to the
124 long-term environmental research observatory OMERE (a French acronym for the
125 Mediterranean Observatory of Water and the Rural Environment). Within rural
126 watersheds, OMERE studies the impacts of anthropogenic forcing and climate change
127 on hydrology, erosion, and water quality (<http://www.umr-lisah.fr/omere>).

128 The El Gameh wadi crosses the 2.45 km² Kamech watershed from the northeast
129 to the southwest. The watershed topography is entirely V-shaped from its middle to the
130 outlet (Figure 1). The slopes are irregular, especially on the southern rim, which has
131 natural embankments induced by sandstone hogbacks. The altitude ranges between
132 94 m and 194 m. The slopes range between 0% and 30%. The soils have sandy-loam
133 textures, with depths ranging from zero to two meters according to the location within
134 the watershed and to the local topography. These swelling soils exhibit shrinkage cracks
135 under dry conditions during the summer [Raclot and Albergel, 2006].

136 [Figure 1 about here]

137 The regional climate is sub-humid with annual values of 600 mm and 1500 mm
138 for precipitation and the Penman-Monteith reference crop evapotranspiration,
139 respectively. The main crops are rainfed. They include winter cereals (durum and bread

140 wheat, barley, oat, triticale) and legumes (chickpeas, favabeans), which can be either
141 harvested or grazed. The steepest parts of the watershed are covered by natural
142 vegetation and used as rangeland for livestock.

143 **2.2. Measurement locations and experimental calendar**

144 The flux measurements were conducted during several months over field A, B and C
145 (Figure 1). In 2004 and 2006, a flux station was installed in field A, located on the
146 northern rim of the watershed. Field A had an area of 1.1 ha with a homogeneous slope
147 of 5° facing south-southeast. This field's northern (and upper) limit was close to the rim
148 top, which forms the watershed edge. In 2005, a flux station was installed in field B,
149 located close to field A. This field had an area of 1.6 ha, and its topographical and
150 pedological conditions were very similar to those of field A. To assess any possible
151 effect of slope orientation on energy fluxes, a second flux station was installed in 2006
152 in field C, located on the southern rim of the watershed and facing northwest. Field C
153 had an area of 2.2 ha and an irregular topography. The averaged slope around its center
154 was approximately 8°. The field's southern (and upper) limit was close to a plateau,
155 located in the middle of the rim. Its northern (and lower) limit had a natural
156 embankment induced by a sandstone hogback. The terrain along-wind cross-sections
157 around flux stations A and C are given in Figure 6 of Zitouna-Chebbi et al. [2012], and
158 the local topography around flux station B was similar to that around flux station A.

159 The flux measurements were collected under conditions of bare soil and
160 vegetation cover, which are detailed in Table 1. In 2004, field A was a wheat crop, and
161 the measurements were collected from March 30 to November 4. In 2006, field A was a
162 favabean crop, and the measurements were collected from March 3 to July 28. In 2005,
163 field B was an oat crop, and the measurements were collected from January 18 to June

164 20. In 2006, field C was a rangeland, and the measurements were collected from April
165 13 to July 27. The corresponding four datasets were labeled A04, A06, B05 and C06,
166 where the letter represents the field, and the two digits represent the year.

167 [Table 1 about here]

168 **2.3. Calculations of land surface energy fluxes in sloping conditions**

169 **2.3.1. Flux station measurements**

170 The sensible and latent heat fluxes, soil heat flux and net radiation were measured with
171 similar flux stations at fields A, B and C. The instruments for each flux station are listed
172 in Table 2. The sonic anemometers and krypton hygrometers collected raw data at a
173 10 Hz frequency. The raw data were stored in the CR23X datalogger, and downloaded
174 every minute to a laptop through the RS232 serial port. The flux measurement stations
175 for dataset A04 and C06 were new. The same flux measurement station was used for
176 dataset A04, B05 and A06. For dataset B05 and A06, the krypton hygrometer did not
177 operate, because of instrumental degradation induced by the alternation between dry
178 and wet periods.

179 [Table 2 about here]

180 For each flux station, the three soil heat flux sensors were distributed two meters
181 away from the station, and were buried between 20 and 50 mm below the soil surface.
182 The net radiometers were installed 1.5 m above the ground. The sonic anemometers, the
183 krypton hygrometers, and the air temperature and humidity probes were installed at the
184 same height above the ground during each period of data acquisition: 1.96 m, 1.78 m,
185 2.05 m and 2.02 m for dataset A04, A06, B05 and C06, respectively. It was a posteriori

186 verified that these measurement heights were appropriate, since they were located
187 within the inertial sublayer (Section 2.5.2).

188 The sonic anemometers were vertically setup and oriented relative to North. The
189 net radiometers were horizontally setup. Instrument setups were carefully checked
190 during the experiment, as described in Zitouna-Chebby et al. [2012]. The latter
191 investigated the accuracy on sonic anemometer alignments according to the
192 experimental protocol and to the analysis of airflow inclination data. The proposed
193 accuracy was better than 2° absolute.

194 Batteries and solar panels powered the data acquisition systems. Because of the
195 high power consumption of the laptop computers, several battery failures occurred, and
196 the 10 Hz data acquisitions were not continuous [Zitouna-Chebby et al., 2012]. After
197 gap filtering, the numbers of 30-minute intervals with 10 Hz data acquisition were 550,
198 1609, 975 and 1286 for datasets A04, A06, B05 and C06, respectively. This
199 corresponded to 10%, 48%, 29% and 52% of daytime observations, evenly distributed
200 throughout the experimental periods.

201 **2.3.2. Calculating airflow inclinations according to wind direction and vegetation** 202 **height**

203 The angles for characterizing the airflow inclinations were calculated from the sonic
204 anemometer data. The calculations were conducted using the planar fit (PF) method
205 [Wilczak et al., 2001] implemented within the ECPACK library version 2.5.22 [van
206 Dijk et al., 2004]. The PF method was chosen since it overcomes the drawbacks of
207 concurrent solutions [Rebmann et al., 2012].

208 The sonic anemometers measured wind speed in three perpendicular directions
209 (labeled u and v in the horizontal plane and w in the vertical plane). In order to virtually
210 align them perpendicularly to the airflow streamlines, the PF method determined the
211 required rotations as defined by three angles: the yaw angle, which was a rotation
212 around the vertical axis that aligned u with the mean wind direction; the pitch angle,
213 which was a rotation around the horizontal axis perpendicular to the wind direction that
214 nullifies the w mean value; and the roll angle, which was a rotation around the
215 horizontal axis parallel to the wind direction. Assuming the airflow streamlines were
216 included in a plane, the latter was fitted to the 10-Hz wind speed components collected
217 over a given time interval.

218 A single plane might not adequately represent the airflow inclinations for
219 different wind directions and vegetation heights. First, local topography induced
220 anisotropic airflows, and the tilt angles (pitch and roll) were supposed to depend upon
221 the wind direction (yaw angle). Second, changes in vegetation height were supposed to
222 influence airflow inclination, because of the cross influences of topography and canopy.
223 Therefore, the 10-Hz EC data were gathered within intervals of wind direction (or wind
224 sectors) and intervals of vegetation height h_v . The numbers of wind sectors and
225 vegetation height intervals to be considered were determined according to analysis
226 results for wind data (Section 2.5.1) and vegetation data (Section 2.5.2).

227 For each dataset (A04, A06, B05 and C06), two calculations were made to
228 ensure that the PF angles were not sensitive to the time interval over which they were
229 estimated. The daily plane calculation consisted of fitting one plane for each wind
230 sector and each day (or a portion of day when the wind direction changed). The single
231 plane calculation consisted of fitting a unique plane over all the data belonging to a

232 given wind sector and to a given $h\nu$ interval (several days for a given wind sector and a
233 given $h\nu$ interval). Similarly to Zitouna-Chebbi et al. [2012], it was a posteriori verified
234 that these two methods provided similar airflow inclinations (Section 3.2).

235 For any plane inclination provided by the PF method, it was possible to calculate
236 the airflow inclination for any observed wind direction (yaw angle). The resulting tilt
237 angles will be referred to as PF pitch and roll angles hereafter. For daily plane
238 calculation, we determined the PF pitch and roll angles for the mean yaw angle of each
239 wind sector. For single plane calculation, we determined the PF pitch and roll angles for
240 any 1° step yaw angle value within the considered wind sector.

241 Uncertainties on airflow inclinations resulted from both the 2° absolute error on
242 EC device alignments (Section 2.3.1) and the errors in planar fit calculations. Both error
243 sources were not considered as critical. First, the daily plane and single plane
244 calculations provided similar airflow inclinations, as shown in Zitouna-Chebbi et al.
245 [2012] and as verified a posteriori in Section 3.2. Second, airflow inclinations were not
246 analyzed in absolute, but in relative through (1) differences in airflow inclinations and
247 topographical slopes, (2) differences in airflow inclinations for upslope and downslope
248 winds, and (3) differences in airflow inclinations for various vegetation heights.

249 **2.3.3. Calculating convective fluxes according to airflow inclination**

250 The convective fluxes (friction velocity u_* , sensible heat flux H and latent heat flux λE)
251 were calculated from the sonic anemometer and the krypton hygrometer data, over 30-
252 minute intervals, by using the ECPACK library version 2.5.22 [van Dijk et al., 2004].

253 Most of the instrumental corrections proposed in the ECPACK library were
254 applied. These corrections addressed (1) the calibration drift of the krypton hygrometer;

255 (2) the linear trends over the 30-minute intervals; (3) the sonic anemometer temperature
256 for humidity; (4) the hygrometer response for oxygen sensitivity; (5) the mean vertical
257 velocity (Webb term); (6) the correction for the frequency response and path averaging;
258 and (7) the tilt corrections for airflow inclination. When correcting the convective fluxes
259 for airflow inclination (item 7), we considered the PF pitch and roll angles derived from
260 the daily plane calculation (Section 2.3.2).

261 A side-by-side comparison of the EC measurement devices was conducted
262 during one month within field A. This comparison aimed at ensuring it was possible to
263 compare the measurements collected within the three fields. Instrumental differences on
264 sensible and latent heat flux (e.g. root mean square difference of 20 W m^{-2}) were within
265 the widely accepted accuracies for the EC data [Foken, 2008; Xu et al., 2013].

266 The quality control of the 30-minute flux data was performed using two standard
267 tests that are routinely employed over flat and sloping terrains, i.e. the Steady State test
268 and Integral Turbulence Characteristics test. These tests permitted to ensure that the
269 theoretical requirements for the EC measurements were fulfilled [Hiller et al., 2008].
270 Following Zitouna-Chebbi et al. [2012], we kept the high and good quality data as
271 defined by Foken et al. [2004] and Rebmann et al. [2005]. For bare soil conditions
272 (respectively vegetation cover conditions), the selection rate was 98% and 69%
273 (respectively 95% and 85%) for the sensible and latent heat flux data.

274 The footprint of each 30-minute flux data was estimated as the ellipsoid from
275 which 90% of the flux originated, by using the approach of Horst and Weil (1992). Each
276 footprint was next superimposed on the digital map of the field boundaries, to quantify
277 each flux contribution from target field (Mauder et al., 2013). Median values for the
278 flux contribution from target field were 67%, 66%, 78% and 80% for datasets A04,

279 A06, B05 and C06, respectively. We did not observe notable differences between
280 northwest and south winds. As compared to bare soil conditions (Zitouna-Chebbi et al.,
281 2012), the flux contributions from target fields were larger for vegetation cover
282 conditions, by 15% relative. These larger contributions were explained by decreasing
283 footprints as vegetation grew. Overall, the flux contributions from target fields were
284 about 75%, whereas the field surveys indicated, in most cases, similar conditions for
285 vegetation canopy cover and soil water status within the target and surrounding fields.

286 **2.3.4. Calculations of net radiation and soil heat flux**

287 The calculations of net radiation R_n and soil heat flux G are detailed in Zitouna-Chebbi
288 et al. [2012].

289 The R_n measurements were corrected for the effects of slope following the
290 procedure proposed by Holst et al. [2005] that relied on solar irradiance and
291 topographical data. Solar irradiance data were derived from measurements collected at
292 the meteorological station located near the watershed outlet (see label M on Figure 1
293 and Section 2.5.1). Topographical data were derived from a four-meter spatial
294 resolution digital elevation model (DEM) obtained by photogrammetry with a stereo
295 pair of panchromatic Ikonos images [Raclot and Albergel, 2006]. The magnitude of the
296 correction on R_n was 50 W m^{-2} on average. A side-by-side comparison of NR-lite net
297 radiometers was conducted during one month within the same field. We observed
298 instrumental differences within the instrumental accuracies, i.e. root mean square
299 difference of 20 W m^{-2} .

300 Soil heat flux G was estimated by averaging the measurements collected by the
301 three soil heat flux sensors distributed around each flux station. No correction was

302 applied for the heat storage between the surface and the sensors, since existing solutions
303 are questionable when considering swelling soils. This was not considered to be a
304 critical issue. Indeed, the resulting error had the same magnitude ($20\text{-}50\text{ W m}^{-2}$) as the
305 measurement uncertainty resulting from the instrumental errors or the spatial variability
306 [Oliosio et al., 2002; Shao et al., 2008; Leuning et al., 2012].

307 **2.4. Calculation of the wind oriented topography**

308 The characterization of the local topography in the vicinity of each flux station is
309 detailed in Zitouna-Chebbi et al. [2012]. It relied on the data derived from the four-
310 meter spatial resolution DEM (Section 2.3.4).

311 First, we defined a rectangle centered on the flux station and oriented along each
312 wind direction (yaw angle). The length and width of the rectangle were derived from the
313 length and width of the ellipsoidal footprints. For the sake of simplicity, we considered
314 the nominal values set by Zitouna-Chebbi et al. [2012] under bare soil conditions, which
315 corresponded to twice the median values of the footprint dimensions (360 m for the
316 length and 120 m for the width). We considered this rectangle size to account for the
317 influence of the upstream / downstream topography on the airflow inclination.

318 The rectangles were calculated for 1° step yaw angle values between 0 and 360° .
319 For each rectangle, a topographical plane was fitted against the corresponding DEM
320 altitude data. The topographical plane equation was next used to define the wind-
321 oriented topography by calculating an along-wind terrain slope geometrically similar to
322 the PF pitch angle (Section 2.3.2) that will be referred to as terrain pitch angle hereafter.

323 It was understood that changes in vegetation height might induce changes in the
324 terrain area that influenced airflow inclination. Therefore, the sensitivity of the terrain

325 pitch angle estimates to the rectangle length was evaluated by using two extreme values
326 for the latter. The first length was 50 m, corresponding to topographical variations at the
327 field scale. The second length was 300 m, corresponding to topographical variations at
328 the hillslope scale. The resulting variation in terrain pitch angle was small, by 0.2° on
329 average.

330 **2.5. Characterization of the experimental conditions.**

331 **2.5.1. Micrometeorological conditions**

332 We characterized the micrometeorological conditions throughout the several months of
333 experiment. We considered the data collected on the four locations within the watershed
334 (Figure 1): two locations on the northern rim (EC data on field A in 2004 and 2006, and
335 on field B in 2005), one location on the southern rim (EC data on field C in 2006) and
336 one location close to the outlet (meteorological station in 2004, 2005 and 2006). Details
337 about the meteorological station are given in Zitouna-Chebbi et al. [2012].

338 Wind speed data, 4 m s^{-1} on average, were twice the worldwide mean values of
339 the Food and Agricultural Organization over lands at 2 m height [Allen et al., 1998].
340 Under bare soil conditions, wind speed did not vary by more than 1 m s^{-1} within the
341 study area. Wind direction data did not depict any diurnal cycle, and they provide
342 similar distributions over the different locations within the watershed. We noted two
343 dominant sectors, as illustrated in Figure 4 in Zitouna-Chebbi et al. [2012]. The first
344 sector corresponded to winds coming from directions between southwest (220°) and
345 east-northeast (70°) directions (clockwise degrees, North is 0°), hereafter referred to as
346 northwest winds. The second sector corresponded to winds coming from the other
347 directions, hereafter referred to as south winds. As the two dominant wind directions

348 were almost perpendicular to the valley axis, the northwest winds corresponded to
349 downslope winds over the northern rim (field A and B) and to upslope winds over the
350 southern rim (field C). The converse applied for the south winds.

351 Micrometeorological conditions were analyzed using the atmospheric stability
352 parameter $\zeta = (z-d)/L_{MO}$, where z is measurement height, d is displacement height and
353 L_{MO} is Monin-Obukhov length. ζ was always negative, with notably few values less
354 than -0.1. When considering each of the dataset A04, A06, B05 and C06 as a whole, ζ
355 median values ranged between -0.052 and -0.018. ζ values were twice to four times
356 more negative for bare soil conditions (between -0.056 and -0.040) as compared to
357 vegetation cover conditions (between -0.029 and -0.014). We did not observe notable
358 differences between northwest and south winds.

359 Overall, the micrometeorological measurements indicated that the wind regime
360 was externally driven and that the stability regime corresponded to forced convection.
361 First, the site experienced large wind speed values. Second, the wind direction did not
362 depend upon the local topography and did not depict any diurnal circulation (i.e. valley
363 breezes). Third, bare soil conditions mostly corresponded to low atmospheric instability,
364 and vegetation cover conditions mostly corresponded to neutral conditions.

365 **2.5.2. Vegetation conditions**

366 We characterized the vegetation conditions throughout the growth cycles for crops
367 (field A in 2004 and 2006, field B in 2005) and rangeland (field C in 2006). For dataset
368 A04 and B05, cereal crops corresponded to homogeneous canopies. For dataset A06
369 and C06, favabean crop and pasture corresponded to heterogeneous canopies. The

370 favabean crop was row structured and thus partially covering. The pasture was a
371 randomly sparse canopy.

372 Vegetation height h_v was measured using a tape measure. For crops
373 (respectively rangeland), a set of 30 (respectively 100) samples per field was
374 considered. Frequency of measurement collection ranged between two and four weeks,
375 in accordance to the vegetation growth observed within the field. A randomly
376 distributed spatial sampling was designed in accordance to each field heterogeneity. For
377 a given day of data collection and a given field, h_v was estimated by calculating over
378 the samples both the averaged value of the measurements and the corresponding
379 standard deviation. We next linearly interpolated the averaged values to obtain daily
380 values between days of data collection.

381 Figure 2 displays the temporal evolution of vegetation height h_v for the datasets
382 A04, A06, B05 and C06. Maximum values for h_v are indicated in Table 1. Two types of
383 temporal evolution were noted. The first type was related to covering vegetation such as
384 the cereal crops for dataset A04 and B05. It was characterized by a growth period,
385 followed by a maturity plateau and next a steep decrease at harvest with vegetation cut.
386 The second type was related to sparse vegetation such as the favabean crop for dataset
387 A06 and the pasture for dataset C06. It differed from the first type after the maturity
388 plateau. For dataset A06, the difference was the absence of vegetation cut (only beans
389 were harvested). Thus, the senescence period induced a slight decrease of vegetation
390 height only, which next combined with the emergence of natural vegetation after
391 rainfalls. For dataset C06, the difference was the occurrence of grazing events, although
392 the latter did not impact the temporal dynamics of vegetation height at the field scale,
393 because of spatial heterogeneities.

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[Figure 2 about here]

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The h_v dataset further permitted to verify the consistency of the experimental setup. The EC devices were setup around 2 m above the ground (Section 2.3.1), which induced a measurement height that was at least twice larger than the vegetation height h_v . Therefore, the measurement height was located within the inertial sublayer above the roughness sublayer, the latter extending from the ground up to $1.43 \times h_v$ [Pattey et al., 2006]. This applied to our experimental conditions (neutral or slightly unstable conditions, as explained in Section 2.5.1), but might not be valid during nighttime and / or under stable or very unstable conditions.

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The h_v dataset was further used to analyze the airflow inclination in relation to the local topography (Section 3.2). For this, three intervals of vegetation height were considered (in meters): $h_v \in [0 - 0.4[$; $h_v \in [0.4 - 0.6[$; $h_v \in [0.6 - 1[$. Finally, vegetation cuts were of interest when seeking any influence of canopy height on airflow inclination, since such temporal discontinuities were expected to induce sharp changes.

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3. Results

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We first address the temporal evolutions of the airflow inclinations as captured by the EC devices, in relation to changes in vegetation height (Section 3.1). We next analyze the influence of both local topography and vegetation height on airflow inclinations (Section 3.2). For this, we compared the airflow inclination against the terrain slope by considering different intervals of vegetation height. Once the EC data are corrected for airflow inclination by discriminating upslope / downslope winds and levels of vegetation height, we finally deal with the reliability of the corrected EC data by analyzing the energy balance closure (Section 3.3).

417 We focus on daytime measurements, since nighttime values of sensible and
418 latent heat fluxes are small at the daily timescale. For airflow inclination analysis, the
419 terrain pitch angle and PF pitch angle had the same sign definition. Positive values of
420 the terrain pitch angle corresponded to upslope winds, and positive values of the PF
421 pitch angle corresponded to upward airflows. Negative values of the terrain pitch angle
422 corresponded to downslope winds, and negative values of the PF pitch angle
423 corresponded to downward airflows.

424 **3.1. Temporal evolutions of airflow inclinations in relation to vegetation height**

425 Figure 3 displays an example of the temporal evolutions of the vegetation height and of
426 the PF pitch angle for upslope and downslope winds. These typical evolutions were
427 obtained with the longest-lasting B05 dataset that included vegetation cut and that
428 depicted the largest temporal changes in vegetation height (Figure 2). As vegetation
429 height increased from 0.15 to 1 m throughout the vegetation growth period, the PF pitch
430 angle decreased from 0 to -5° for downslope winds; and from 5.5 to 3° for upslope
431 winds. The changes in PF pitch angle were twice larger for downslope winds (5°) than
432 for upslope winds (2.5°). Immediately after vegetation cut, both the vegetation height
433 and the PF pitch angle returned to their initial values at the beginning of the growing
434 period.

435 [Figure 3 about here]

436 The behaviors we observed with the A04 dataset (data not shown) were very
437 similar to those reported when analyzing the B05 dataset. On the one hand, the two
438 datasets depicted sharp changes in PF pitch angle after vegetation cut, for both upslope
439 and downslope winds. On the other hand, the two datasets depicted larger changes in PF

440 pitch angle for downslope winds than for upslope winds. Different behaviors were noted
441 with the A06 and C06 datasets (data not shown): lower variations of PF pitch angle
442 throughout the experiment were related to slighter evolutions of vegetation height, as
443 previously noted (Figure 2).

444 **3.2. Airflow inclinations as driven by topography and vegetation height**

445 For each dataset (A04, A06, B05 and C06), the planar fit (PF) angle calculation was
446 twofold (Section 2.3.2). The daily plane calculation yielded between more than 10 and
447 less than 20 daily planes, according to the number of 30-minute intervals of 10-Hz data
448 collected (Section 2.3.1). The single plane calculation yielded two planes corresponding
449 to the northwest and south wind sectors for each of the three $h\nu$ intervals.

450 Figure 4 compares the terrain slopes and the airflow inclinations, as a function
451 of wind direction, for each of the four datasets (A04, A06, B05 and C06). The
452 continuous lines represent the terrain pitch angle along the wind direction, as derived
453 from the DEM data. The airflow inclinations are represented by the PF pitch angles that
454 are derived either from the daily plane calculation (symbols) or from the single plane
455 calculations (dashed or dotted lines according to vegetation height $h\nu$).

456 [Figure 4 about here]

457 Regardless of dataset (A04, B05, A06 and C06), wind sector (northwest and
458 south) and $h\nu$ interval, PF pitch angles given by the daily plane calculation and the
459 single plane calculation were in close agreement. Changes in vegetation height induced
460 changes in pitch angle, as indicated by the splitting of each dataset into the three $h\nu$
461 intervals. Further, positive values for PF pitch angle indicate that upward airflows

462 corresponded to upslope winds, and negative values for pitch angle indicate that
463 downward airflows corresponded to downslope winds.

464 Three specific behaviors were observed through the analysis of the PF pitch
465 angle as a function of vegetation height and of upslope / downslope winds.

466 • When considering upslope winds with bare soil and low vegetation heights
467 ($h_v < 0.4$ m) for the datasets A04, B05 and A06, the PF pitch angles were close to
468 the terrain pitch angles, which indicated that the airflow inclinations were close to
469 the terrain slope. Increase in vegetation height ($h_v > 0.6$ m) induced a slight
470 decrease in PF pitch angle, between 1 and 2°, which indicated that the airflow
471 inclination tended to be less tilted than the terrain slope.

472 • When considering downslope winds under conditions of bare soil and low
473 vegetation heights ($h_v < 0.4$ m) for the datasets A04, B05 and A06, the PF pitch
474 angle was larger than the terrain pitch angle, of about 3 to 5°. In this case, the PF
475 pitch angle was closer to nil, and thus the airflow inclination was close to the
476 horizontal plane. Increase in vegetation height ($h_v > 0.6$ m) induced a decrease in PF
477 pitch angle of about 4°. Then, the latter almost equaled the terrain pitch angle,
478 which indicated that the airflow inclination came closer to the terrain slope.

479 • When considering dataset C06 that corresponded to conditions of low vegetation
480 height only ($h_v < 0.4$ m), there was a good agreement between terrain pitch angle
481 and PF pitch angle for both upslope and downslope winds, which indicated that
482 airflow inclination almost followed the terrain slope.

483 Overall, the following trends can be reported. For upslope winds, airflow inclination
484 was close to the terrain slope under conditions of bare soil and low vegetation height,

485 and it was less tilted as vegetation height increased. The converse was observed for
486 downslope winds: airflow inclination was only slightly tilted under conditions of bare
487 soil and low vegetation height, and it was more tilted as vegetation height increased,
488 thus coming closer to the terrain slope. As compared to upslope winds, we observed
489 larger changes in airflow inclination for downslope winds, when vegetation height
490 increased. The behaviors reported here were systematically observed for dataset A04,
491 B05 and A06. For dataset C06 that corresponded to low vegetation height, we noted a
492 systematic agreement between airflow inclination and terrain slope, regardless of
493 upslope and downslope winds.

494 We next attempted to isolate the relation between vegetation height and airflow
495 inclination, by characterizing the shifted pitch angle (defined as the difference between
496 PF pitch angle and terrain pitch angle) as a function of the vegetation height $h\nu$
497 (Figure 5). or this, we considered the dataset B05 that spread over the vegetation growth
498 cycle, thus capturing a large dynamics of vegetation height. Figure 5 shows that the
499 shifted pitch angle was strongly related to $h\nu$, with a larger dynamics for downslope
500 winds (changes of about 4.5°) as compared to upslope winds (changes of about 1.5°).
501 The relation between shifted pitch angle and $h\nu$ appeared to be linear, with coefficients
502 of determination R^2 ranging from 0.68 for upslope winds to 0.85 for downslope winds.
503 When considering the other datasets (data not shown), the trends were less pronounced
504 because of lower vegetation dynamics. Nevertheless, the linear regressions obtained for
505 dataset B05 were similar to those obtained for dataset A04, where the latter spread
506 over the senescence period and the harvest time only.

507 [Figure 5 about here]

508 **3.3. Correction of convective fluxes and energy balance closure**

509 The EC measurements of convective fluxes were corrected for airflow inclination. The
510 tilt correction was conducted by using the PF pitch angles derived from the daily plane
511 calculation, thus discriminating between upslope and downslope winds, and
512 discriminating between levels of vegetation height (Section 2.3.3). For upslope winds
513 (respectively downslope winds), the tilt correction increased (respectively decreased) H
514 and λE by 37% (respectively 17%) on average over the datasets. The magnitude of the
515 tilt correction was larger on average as the airflow inclination was larger. For field A
516 with upslope winds, the tilt correction increased H and λE by 30%, and by 40% on field
517 C with steeper slopes. For field B with downslope winds, the magnitude of the tilt
518 correction was lower with less tilted airflows over low vegetation ($h_v < 0.4$ m), by 20%
519 for H , as compared to more tilted airflows over tall vegetation ($h_v > 0.6$ m).

520 We analyzed the energy balance closure by comparing the convective fluxes CF
521 ($CF = H + \lambda E$) against the available energy $AE = Rn - G$. Although the usefulness of
522 such analysis as a quality test may be debatable [Lee et al., 2004], it was considered as
523 an interesting comparison of independent measurements. The data to be compared were
524 those calculated over the 30-minute intervals (Section 2.3.3 and Section 2.3.4).

525 Since no latent heat flux data were collected for the datasets A06 and B05,
526 because of the krypton hygrometer inoperability, the energy balance closure could be
527 analyzed for datasets A04 and C06 only. The number of available observations for
528 assessing the energy balance closure was constrained by the availability of the four
529 components of the energy balance (net radiation Rn , soil heat flux G , sensible H and
530 latent λE heat fluxes) and by the quality control filtering (Section 2.3.3).

531 The analysis of energy balance closure was conducted by discriminating
532 between upslope and downslope winds and by discriminating between bare soil and
533 vegetation cover. Following Zitouna-Chebbi et al. [2012] who addressed energy balance
534 closure for bare soil conditions, we considered here the results obtained for both bare
535 soil and vegetation cover conditions (Figure 6). The corresponding statistical indicators
536 are given in Table 3.

537 [Figure 6 about here]

538 [Table 3 about here]

539 The energy balance closure, as expressed through the energy balance ratio
540 $EBRAT = CF / AE$, ranged from 83% to 94%, with the exception of the downslope
541 winds for dataset C06 that corresponds to 73% for both bare soil or vegetation cover.
542 Also, CF systematically underestimated AE for large values.

543 The energy balance closure was similar if considering bare soil or vegetation
544 cover conditions, with the following statistical indicators (defined in Table 3 caption):
545 energy balance residual $EBRES$ ranged from 20 to 95 $W m^{-2}$, root mean square
546 difference $RMSD$ ranged from 45 $W m^{-2}$ to 110 $W m^{-2}$, coefficient of determination R^2
547 ranged from 0.88 to 0.95, slope and offset values for the linear regression from CF to
548 AE ranged from 0.65 to 0.8 and from 20 to 46 $W m^{-2}$, respectively.

549 We finally analyzed the energy balance closure as a function of the upslope and
550 downslope winds. For dataset A04, the statistical indicators were slightly better with
551 downslope winds as compared to upslope winds (Table 3): $RMSD$ was 20 $W m^{-2}$ lower,
552 $EBRAT$ was 10% larger, $EBRES$ was twice lower, and the slope value for the linear
553 regression from CF to AE was 10% larger. For dataset C06, conversely to A04, the

554 statistical indicators were better for the upslope winds as compared to the downslope
555 winds (Table 3): *RMSD* was 60 W m^{-2} lower, *EBRAT* was 20% larger, *EBRES* was four
556 to five times lower, and the slope value for the linear regression from *CF* to *AE* was
557 15% larger.

558 **4. Discussion**

559 The trends we observed when analyzing the temporal evolutions of airflow inclination
560 as captured by the EC based pitch angles were consistent with the dynamics of
561 vegetation height. On the one hand, sharp changes in PF pitch angles systematically
562 occurred after harvest for datasets A04 and B05, where vegetation cut reset airflow
563 inclination to its initial value at the beginning of the crop growth cycle. On the other
564 hand, lower variations of PF pitch angle throughout the experiment for datasets A06 and
565 C06 were ascribed to the slighter evolutions of vegetation height: the harvest was
566 restricted to bean collection for dataset A06, and the vegetation dynamics of the pasture
567 resulted in slight changes for dataset C06. These observations suggested that changes in
568 airflow inclinations were strongly linked to changes in vegetation height. We did not
569 ascribe changes in airflow inclinations to changes in atmospheric stability conditions,
570 since the latter depicted a narrow range, between neutral and very low instability
571 regimes.

572 When analyzing airflow inclination over bare soils, upslope winds induced
573 behaviors similar to those observed under flat conditions, since the streamlines followed
574 the local topography. A different behavior was observed for downslope winds with
575 datasets A04, A06 and B05. This was consistent with theoretical works on streamline
576 dilatation in relation to the non-separated sheltering effect [Belcher et al., 1993], where
577 fields A and B were located in the lee of the hilltop. Further, momentum absorption by

578 the canopy foliage explained changes in airflow inclinations when vegetation height
579 increased, from the terrain slope to less tilted planes under upslope winds, and from
580 nearly the horizontal plane to the terrain slope under downslope winds.

581 Two types of airflow regime were identified according to the classification
582 proposed by Poggi et al. [2008], which is based on the ratio of vegetation height h_v to
583 the canopy adjustment length scale L_c (deep or shallow canopies), and on the ratio of
584 the along-wind hill length L_h to the hill height H_h (narrow or long hills). When
585 considering the two watershed rims and the two dominant wind directions, L_h
586 (respectively H_h) ranged between 200 and 400 m (respectively 40 and 60 m). Following
587 the aforementioned classification, the airflow regimes we observed corresponded to
588 regime IV (shallow canopy) at the beginning of the growth cycle ($L_h / (2 L_c)$ around 3.5
589 and h_v / L_c around $6 \cdot 10^{-4}$), and to Regime I (deep canopy) or IV (shallow canopy) at the
590 end of the growth cycle ($L_h / (2 L_c)$ between 60 and 220 and h_v / L_c between 0.1 and
591 0.7). Following Poggi et al. [2008], we can conclude that (1) airflow above the canopy
592 was primarily driven by the topography, (2) the changes in airflow inclination when
593 vegetation grew could be ascribed to increase in momentum absorption by the canopy
594 foliage when the latter became thicker, and (3) the advection remained small.

595 When applying the tilt correction in the calculation of H and λE , it was
596 necessary to discriminate not only between upslope and downslope winds but also
597 between vegetation heights. As more tilted airflows induced larger corrections, fitting a
598 single plane for both upslope and downslope winds and regardless of vegetation height
599 would induce intermediate values for PF pitch angle, and therefore would provide
600 wrong tilt corrections for H and λE .

601 The results obtained for energy balance closure also emphasize the relevance of
602 discriminating upslope / downslope winds and intervals of vegetation height, when
603 applying the tilt correction on convective fluxes. For upward airflows, the correction
604 increased the convective fluxes by 30% relative and thus improved by the same
605 magnitude the energy balance closure that was characterized by an underestimation of
606 available energy. For downward airflows on field A, the correction decreased the
607 convective fluxes, thus making their sum lower than available energy. The unique case
608 for which we did not observe any improvement is related to downward airflows on field
609 C, where the tilt correction increased the underestimation of available energy.

610 No correction was applied on soil heat flux measurements for soil heat storage
611 between the surface and the sensors, since existing solutions are questionable when
612 considering swelling soils. Also, canopy heat storage was not taken into account, since
613 it is both difficult to estimate and usually disregarded for agricultural crops. Neglecting
614 both canopy and soil heat storage resulted in overestimating available energy and thus
615 increasing energy balance disclosure. On average, including canopy and soil heat
616 storage would decrease available energy by 1 - 3% and 2 - 5% relative, respectively
617 (Wang et al., 2010), and thus would raise energy balance ratio (EBRAT) between 88%
618 and 99%, especially at mid-day. This EBRAT increase indicates the effectiveness of the
619 correction method we proposed.

620 Overall, and regardless of the considered case (field, year, wind direction, bare
621 soil or vegetation cover), the statistical indicators for energy balance closure after tilt
622 corrections were comparable to those reported in previous studies [Wilson et al., 2002;
623 Hammerle et al., 2007; Foken, 2008; Hendricks Franssen et al., 2010; Wang et al.,
624 2010; Malone et al., 2014] that considered different topographies (flat and mountainous

625 topographies) and different vegetation cover conditions (bare soils and various
626 canopies).

627 Several explanations can be proposed for the different results we observed for
628 field C, including (1) the complex topography of the southern rim, (2) the differences in
629 hill shapes and sizes within the southern rim, or (3) the locations of the EC flux stations
630 within the hillslopes for downslope winds: fields A and B were located in the lee of the
631 northern rim top and close to it, whereas field C was located further from the southern
632 rim top. Besides, Finnigan and Belcher [2004] also reported asymmetry in the flow
633 between upslope and downslope winds, as observed on field A but not on field C.
634 However, any comparison with outcomes from modeling studies should be carefully
635 conducted. On the one hand, these modeling studies addressed simple situation such as
636 single or periodic two-dimensional hills. On the other hand, the experimental study we
637 report here addressed complex hilly structures with various hill shapes.

638 **5. Concluding remarks**

639 Main outcomes from the current study are twofold. First, airflow inclination was
640 strongly influenced by the combined effects of wind direction, topography and
641 vegetation height. Changes in airflow inclination were observed for upward and
642 downward airflows, and for different levels of vegetation height. Second, when
643 applying planar fit tilt corrections on EC measurements, it was necessary to discriminate
644 not only between upward and downward airflows, but also between vegetation height
645 intervals. This discrimination permitted to improve the EC measurements and thus to
646 obtain reliable estimates of daytime energy fluxes over hilly crop fields.

647 The experimental observations we reported here can be ascribed to specific
648 airflow regimes previously reported in theoretical studies, such as streamline dilatation /
649 contraction and non-separated sheltering effect, momentum absorption by the canopy
650 foliage, and relative location within the hillslope. This consistency between
651 experimental and theoretical outcomes increases our confidence in the measurements
652 we discussed here.

653 Topography and wind direction can vary significantly from one place to another
654 within any hilly watershed, with changing influences on airflow inclination and planar
655 fit tilt corrections for flux measurements. Therefore, it is necessary to account for
656 possible influence of wind direction and vegetation height on airflow inclination, when
657 applying planar fit tilt corrections over hilly terrains.

658 The experimental observations we reported here were focused on the
659 observation of land surface energy and mass (water vapor) fluxes. However, it is most
660 likely that these observations do also apply when observing other mass fluxes such as
661 carbon dioxide, methane or volatile organic compounds. We therefore recommend to
662 conduct such investigations.

663 Finally, our experimental observations cast into doubt the relevance of using
664 common modeling tools within hilly crop fields, since these tools were developed for
665 flat conditions. As mentioned by Finnigan and Belcher [2004], canopy roughness length
666 is likely to change with accelerating and decelerating flow over hills, with consequences
667 on aerodynamic resistance. Investigating such questions will enable the expansion of
668 the recent modeling works by Rana et al. [2007], and should imply new formulations
669 for the operational FAO-56 method proposed by Allen et al. [1998].

670

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684

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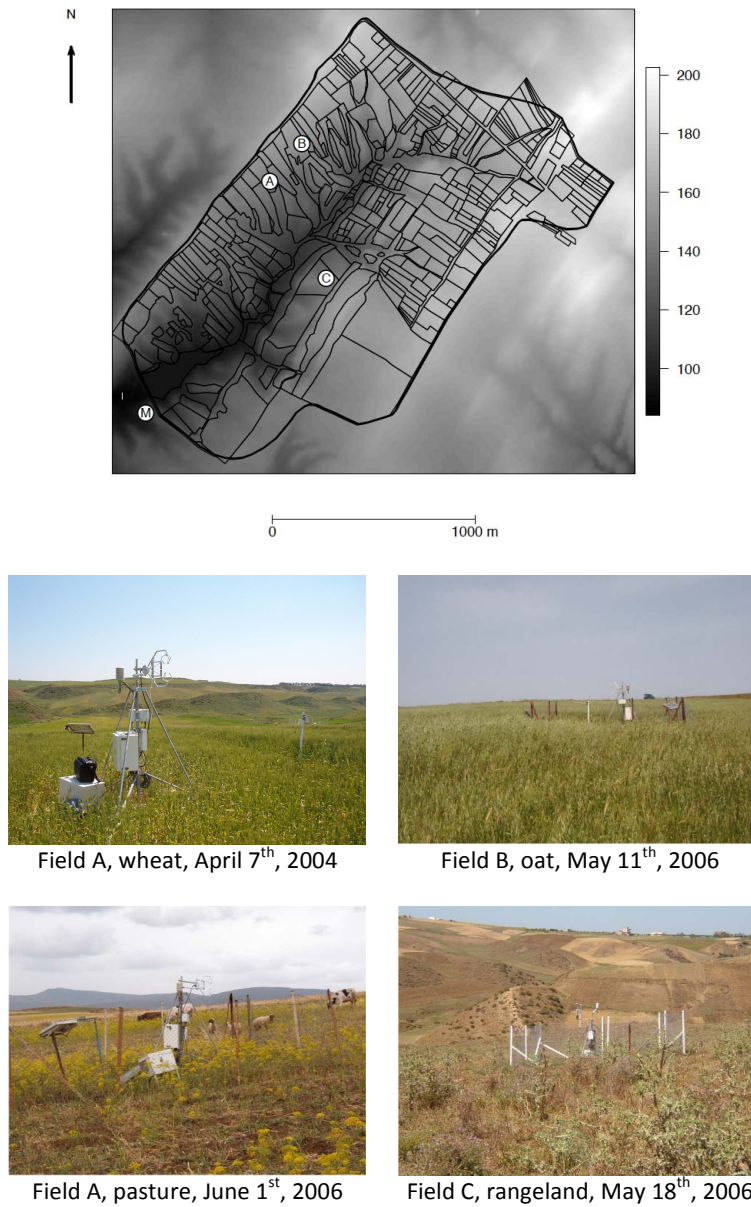
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909 **List of Figures**

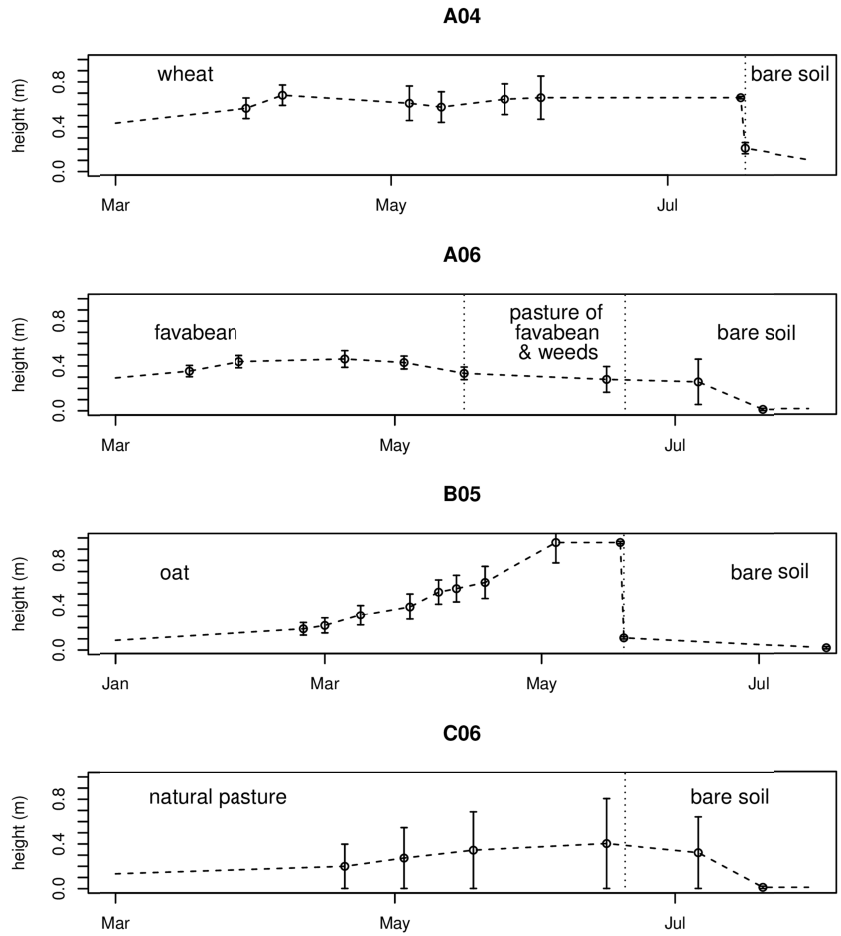
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912 Figure 1: (top) Topography of the Kamech watershed deduced from a 4-m spatial
 913 resolution digital elevation model (DEM). Altitude above sea level is given in meters
 914 (right gray-scale bar). The thick black line represents the watershed outline, and the thin
 915 black lines represent the field limits. The white circles indicate the locations of the
 916 meteorological station (M) and of the flux stations on fields A, B and C. (Middle and
 917 bottom) Pictures of each experimental setup within field A in 2004, field B in 2005,
 918 field A in 2006 and field C in 2006.

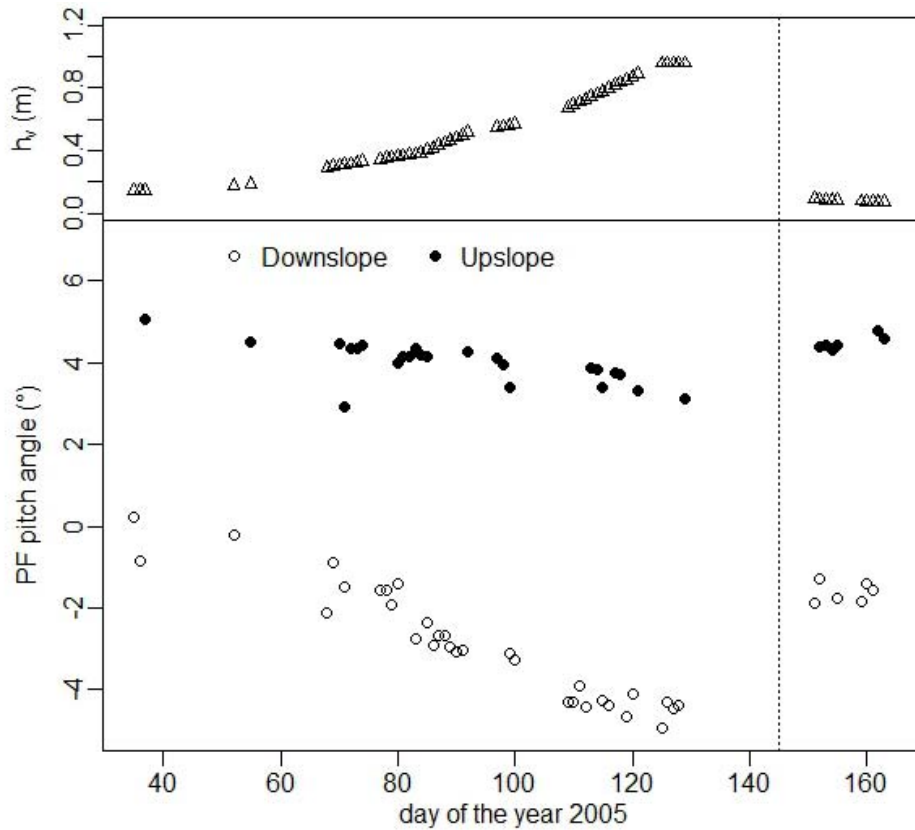
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931 Figure 2: Chronicles of vegetation height h_v . From top to bottom are sub-plotted
 932 estimates for field A in 2004, field A in 2006, field B in 2005 and field C in 2006.
 933 Points represent averaged values of vegetation height measurements over the samples
 934 collected within a given field on a given day. Vertical bars represent standard deviations
 935 over the samples. Dashed lines represent temporally interpolated values. Vertical dotted
 936 lines indicate specific changes detailed hereafter. Vertical dotted lines in subplot A04
 937 and B05 represent the harvest times. First vertical dotted line in subplot A06 represents
 938 the harvest time and the subsequent start of the pasture period (only beans were
 939 harvested, no vegetation cut). Second vertical dotted line in subplot A06 and vertical
 940 dotted line in subplot C06 represent the start of periods with very sparse vegetation.

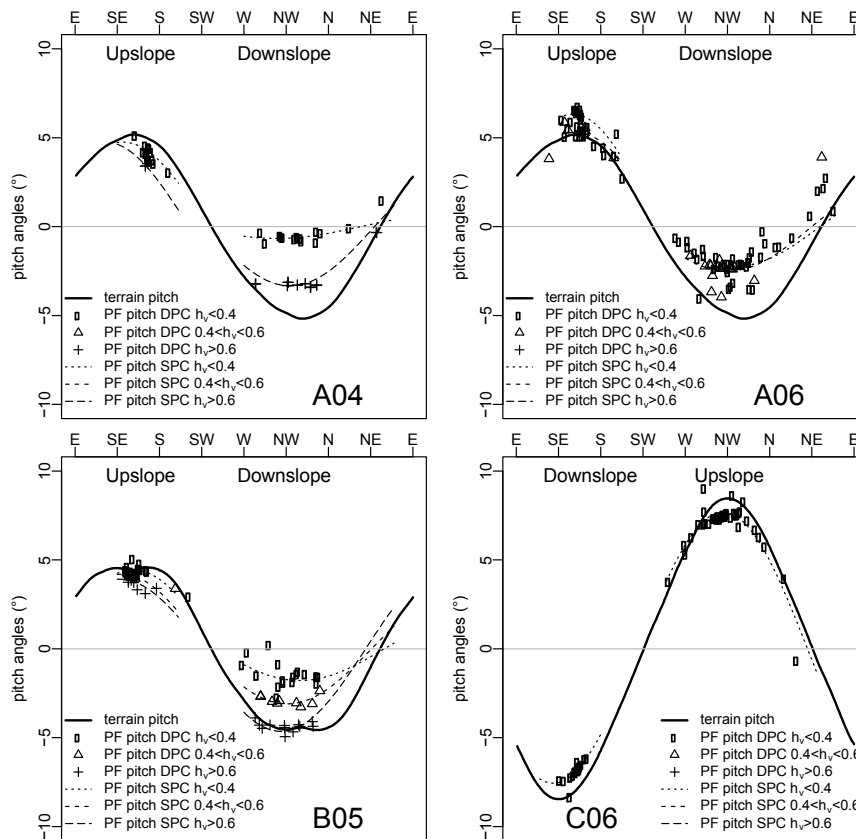
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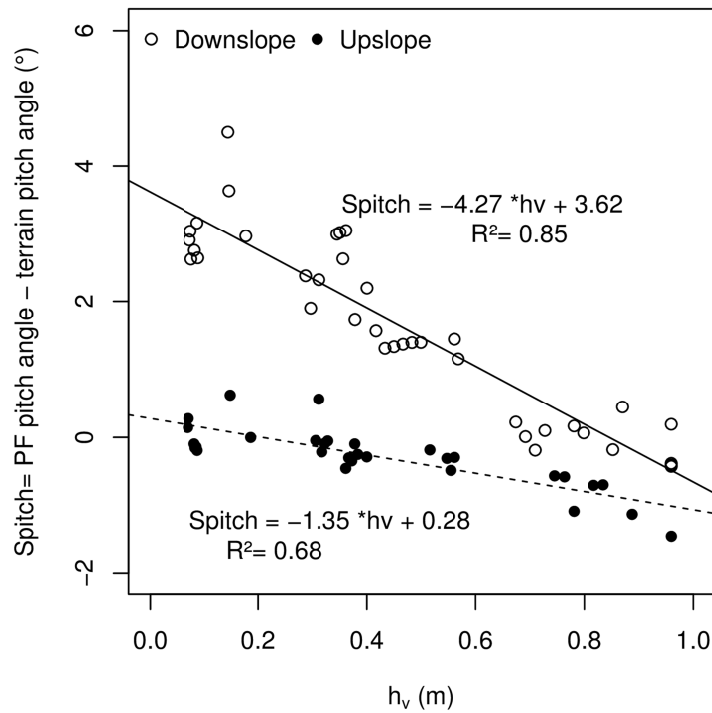
933 Figure 3: Temporal evolutions of vegetation height h_v (top subplot), and of planar fit
 934 (PF) pitch angle (bottom subplot) for upslope winds (solid circles) and downslope
 935 winds (opened circles). Vertical dotted lines indicate the harvest date. Measurements
 936 from the B05 dataset, with downslope winds from north and upslope winds from south.

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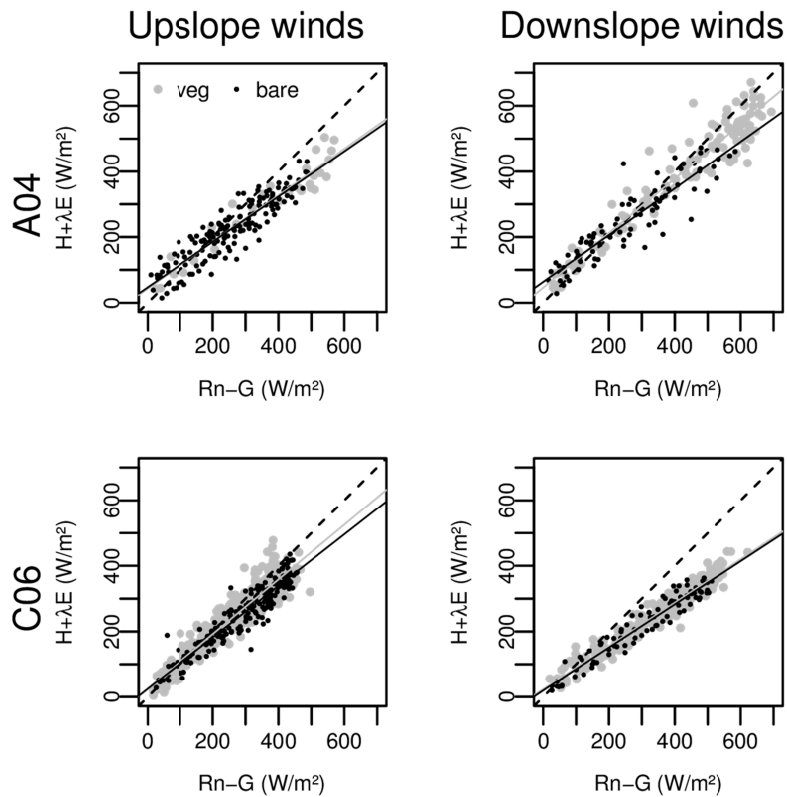
939 Figure 4: Compared evolution of the planar fit derived pitch angles and the terrain pitch
 940 angles (y-axis) with respect to the wind direction (x-axis, 0° is north, 90° is east) for
 941 dataset A04 (top left subplot), A06 (top right subplot), B05 (bottom left subplot) and
 942 C06 (bottom right subplot). The continuous curves represent the terrain pitch angle, as
 943 derived from the DEM data. The planar fit-derived pitch angles evaluated for each day
 944 and each wind sector (labeled PF pitch DPC for daily plane calculation) are represented
 945 by symbols (circles if $h_v \in [0 - 0.4[$, triangles if $h_v \in [0.4 - 0.6[$, and crosses if $h_v \in$
 946 $[0.6 - 1[$, with h_v in meters). The planar fit derived pitch angles for all of the data
 947 belonging to both a given wind sector and a given h_v interval (labeled PF pitch SPC for
 948 single plane calculation) are represented with portions of discontinuous curves (long
 949 dashed if $h_v \in [0 - 0.4[$, short dashed if $h_v \in [0.4 - 0.6[$, and dotted if $h_v \in [0.6 - 1[$,
 950 with h_v in meters). In this last case, wind sectors (south and northwest) are indicated
 951 with x-axis.



954

960 Figure 5: Characterization of the shifted pitch angle (defined as the difference between
 961 PF pitch angle and terrain pitch angle) as a function of the vegetation height h_v . We
 962 considered the B05 dataset that spread over the vegetation growth cycle. Continuous
 963 line is the regression line over the data corresponding to downslope winds (opened
 964 circles). Dashed line is the regression line over the data corresponding to upslope winds
 965 (solid circles).

961



962

971 Figure 6: Energy balance closure analysis that compares the convective fluxes
 972 $CF = H + \lambda E$ (y-axis) against the available energy $AE = Rn - G$ (x-axis). The left
 973 column corresponds to upslope winds and the right column corresponds to downslope
 974 winds. The first line corresponds to the dataset A04, and the second line corresponds to
 975 the dataset C06. We selected conditions of both bare soil (black circles labeled "bare" in
 976 legend) and vegetation cover (gray circles labeled "veg" in legend). Each symbol
 977 corresponds to a 30-minute interval measurement. For each scatterplot, the dashed line
 978 is the 1:1 line, and the continuous line is the y-axis data versus x-axis data regression
 979 line (regression coefficients are given in Table 3).

972

972 **List of Tables**

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974

975 Table 1: Presentation of the experimental conditions for the four datasets

Dataset label	Field label	Land use	Measurement period	Phenological stage	Maximum vegetation height (m)
A04	A	Durum wheat	30/03/04 → 16/07/04	From heading to yellow ripeness	0.68
			17/07/04	Harvest	
		Bare soil	18/07/04 → 04/11/04	-	
A06	A	Favabean	03/03/06 → 15/05/06	Full development	0.46
			16/05/06	Harvest	
		Favabean and weeds	17/05/06 → 20/06/06	Senescence	
		Bare soil	21/06/06 → 28/07/06	-	
B05	B	Oat	18/01/05 → 24/05/05	From emergence to heading	0.96
			25/05/05	Harvest	
		Bare soil	26/05/05 → 20/06/05	-	
C06	C	Rangeland	13/04/06 → 20/06/06	From greenness to senescence	0.40
		Bare soil	21/06/06 → 27/07/06	-	

976

977

978 Table 2: Listing of the instruments, acquisition and storage frequency for each flux
 979 station

Instrument type	field A Year 2004	field A Year 2006	field B Year 2005	field C Year 2006	Acquisition frequency	Storage frequency
Datalogger	CR23X (Campbell Scientific Inc., USA)					
Net radiometer	NR-lite (Kipp & Zonen, the Netherlands)				1 s	30 mn
Soil heat flux sensors	HFP01 (Hukseflux, the Netherlands) (three per field)				1 s	30 mn
Thermo-hygrometer probe	HMP45C (Vaisala, Finland)				1 s	30 mn
Sonic anemometer	CSAT3 (Campbell Scientific Inc., USA)			Young-81000V (R.M. Young, USA)	10 Hz	10 Hz
Krypton hygrometer	KH20 (Campbell Scientific Inc., USA)	(KH20 was off)		KH20 (Campbell Scientific Inc., USA)	10 Hz	10 Hz

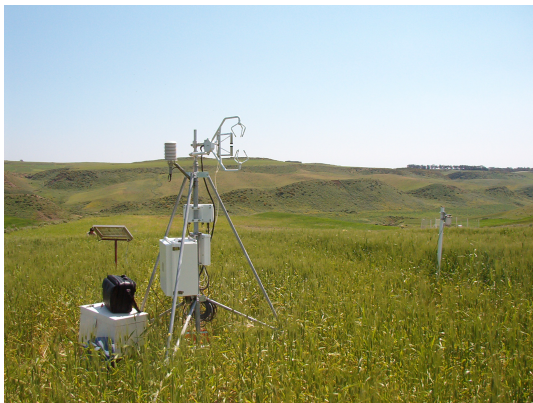
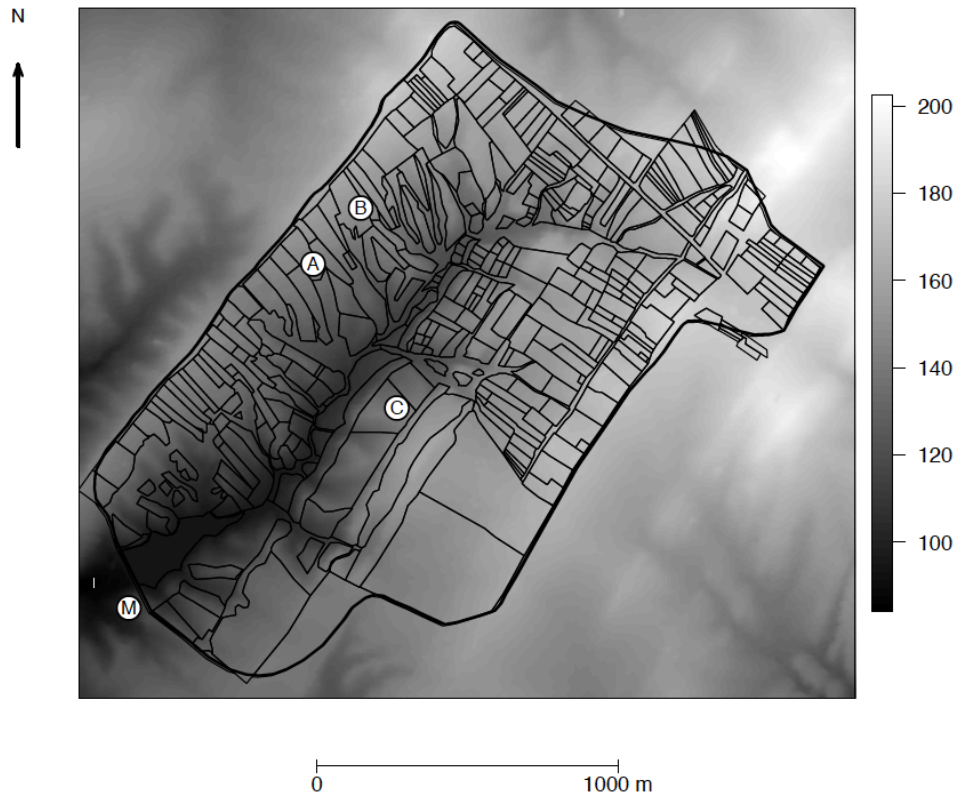
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981 Table 3: Statistical indicators for characterizing the energy balance closure ^a

	Conditions of bare soil				Conditions of vegetation cover			
	A04		C06		A04		C06	
	Up	Down	Up	Down	Up	Down	Up	Down
N	155	99	233	120	32	132	328	240
Slope <i>a</i>	0.69	0.71	0.73	0.64	0.71	0.83	0.83	0.66
Offset <i>b</i> (W m ⁻²)	47.0	63.3	44.8	28.2	43.3	46.0	25.1	23.0
R ²	0.82	0.84	0.88	0.93	0.92	0.93	0.88	0.95
RMSD (W m ⁻²)	63.7	65.5	55.6	100.9	87.4	62.6	44.7	110.8
URMSD (W m ⁻²)	39.6	47.4	34.9	25.6	38.0	46.8	35.8	23.3
<i>EBRAT</i> (W m ⁻²)	0.87	0.95	0.90	0.73	0.83	0.94	0.93	0.73
<i>EBRES</i> (W m ⁻²)	32.7	12.2	26.9	81.2	61.3	25.1	19.0	96.0

982 ^a We compare the convective fluxes *CF* ($CF = H + \square E$) as the y-axis variable against
983 the available energy *AE* ($AE = Rn - G$) as the x-axis variables. *N* is the number of data
984 (30-minute intervals). Terms *a* and *b* are, respectively, the slope and the intercept of the
985 $y = a x + b$ linear regression (gray and black continuous lines for vegetation and bare
986 soil, respectively, in Figure 6). R² is the coefficient of determination between *y* and *x*.
987 *RMSD* is the root mean square difference between *y* and *x*. *URMSD* is the unsystematic
988 *RMSD*, defined as the scattering around the $y = a x + b$ linear regression. *EBRAT* is the
989 energy balance ratio defined as $EBRAT = CF / AE$. *EBRES* is the energy balance
990 residual, defined as $EBRES = AE - CF$. Label "Up" is for upslope winds, and label
991 "Down" is for downslope winds. The metrics used here were selected from among those
992 reviewed by Kustas et al. (1996) and Wilson et al. (2002). The results for bare soil are
993 from Zitouna-Chebbi et al. (2012).

994



Field A, wheat, April 7th, 2004



Field B, oat, May 11th, 2006

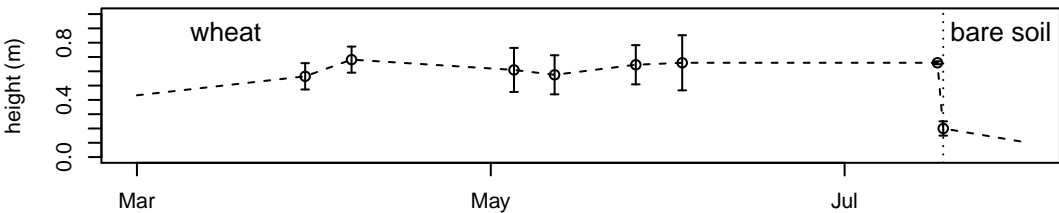


Field A, pasture, June 1st, 2006

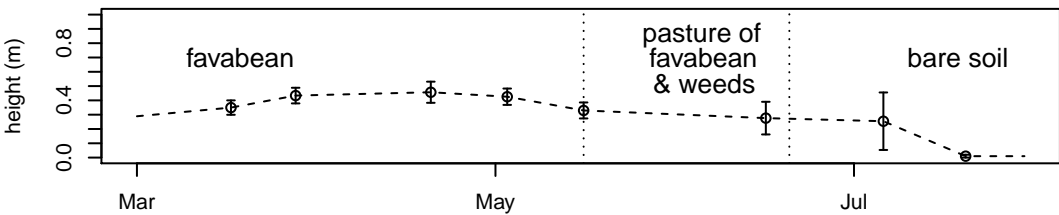


Field C, rangeland, May 18th, 2006

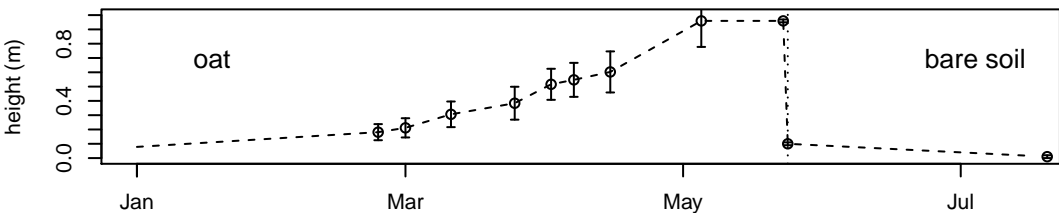
A04



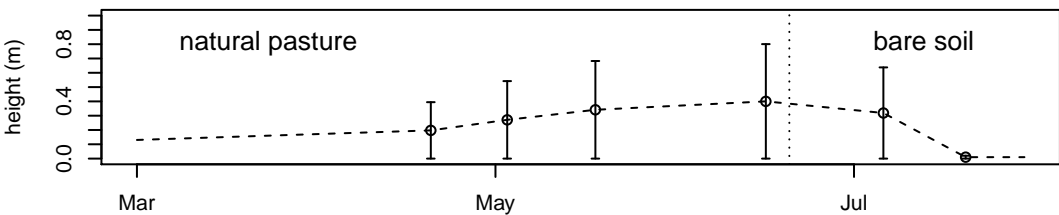
A06

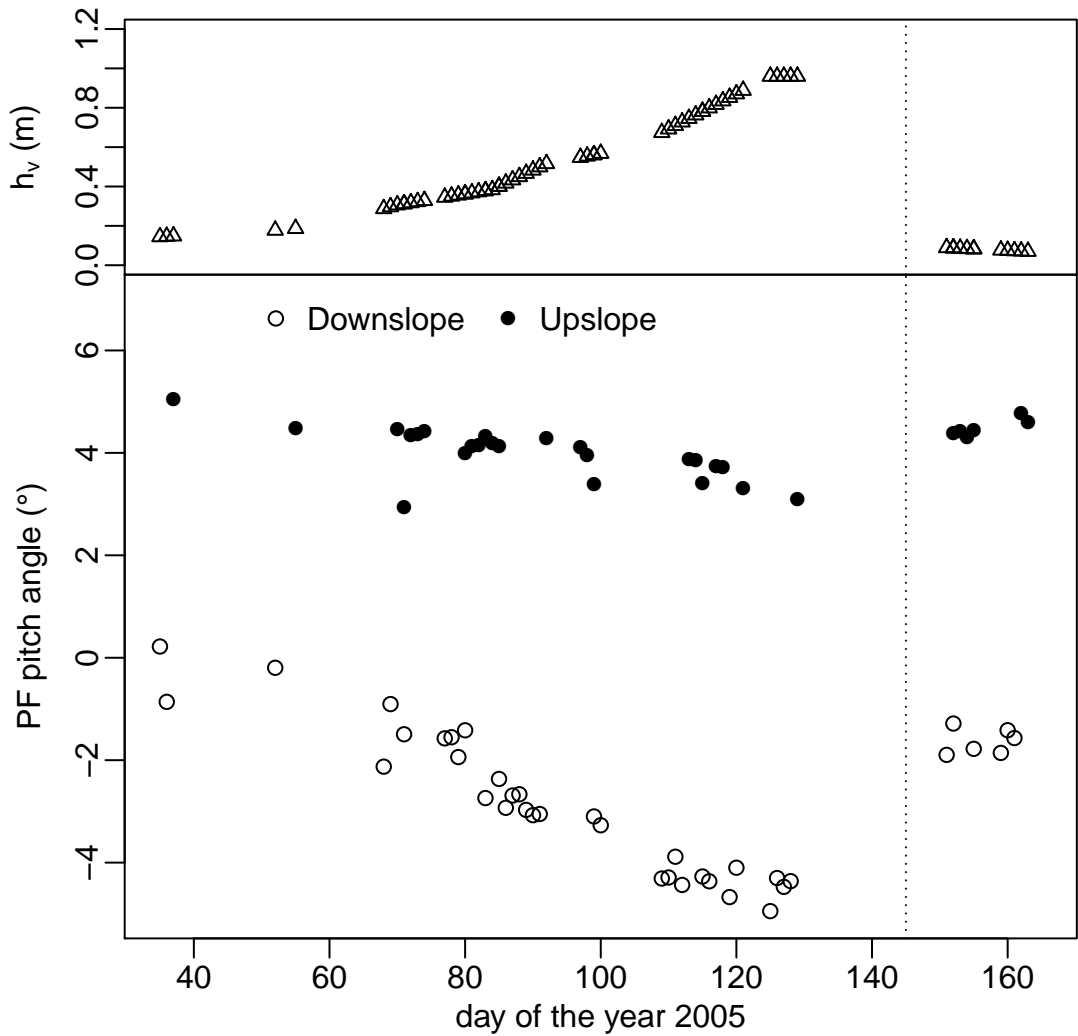


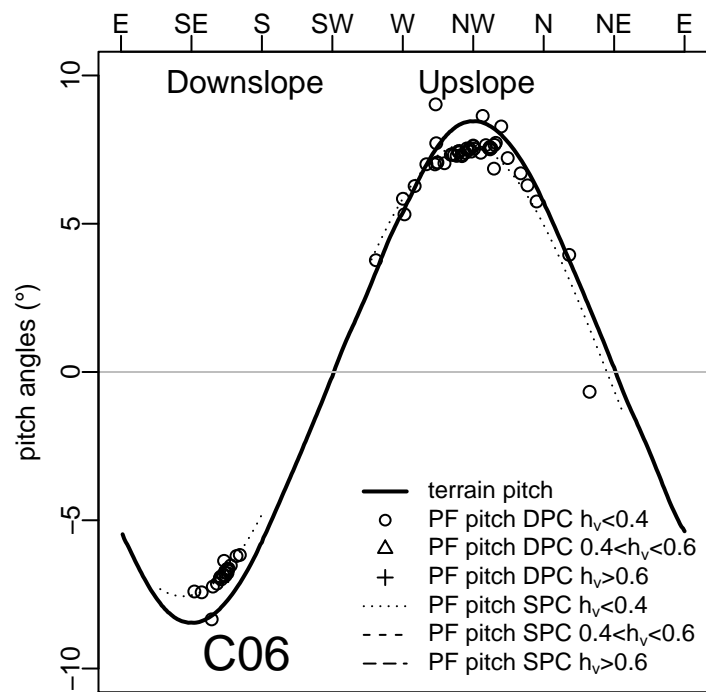
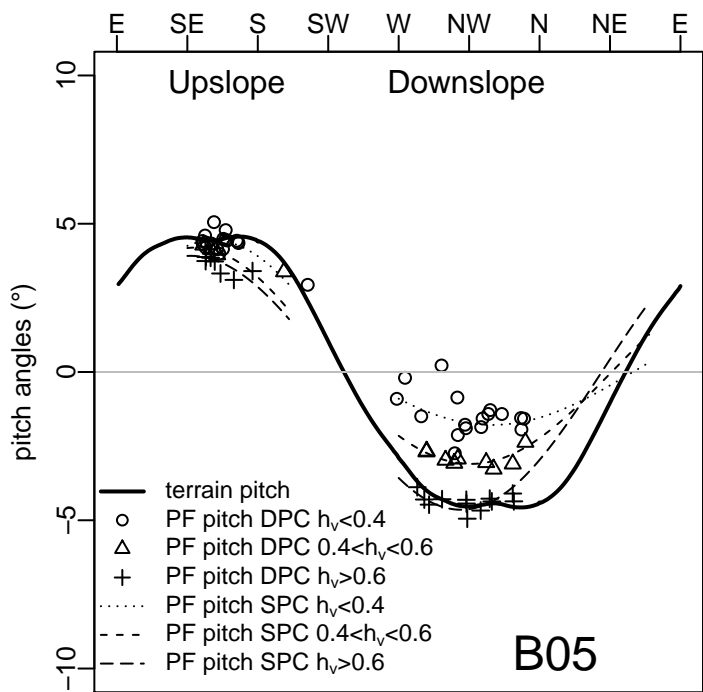
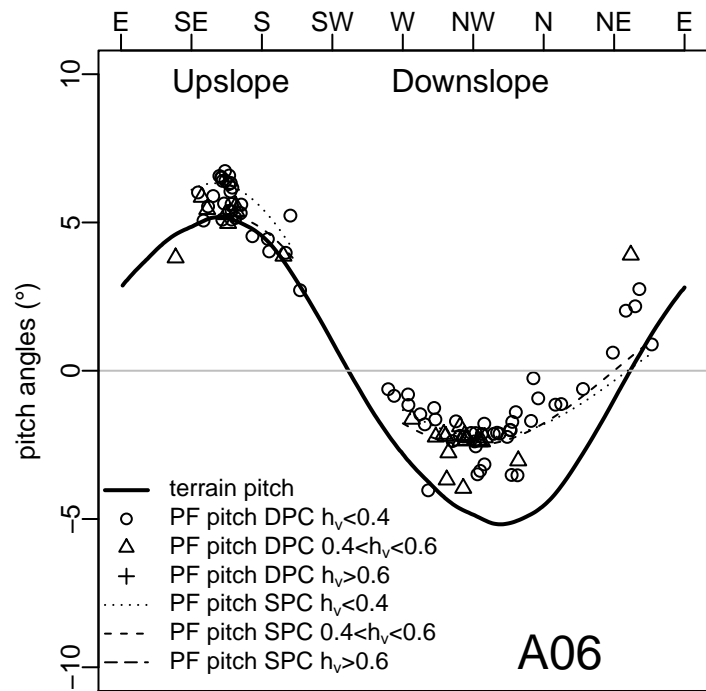
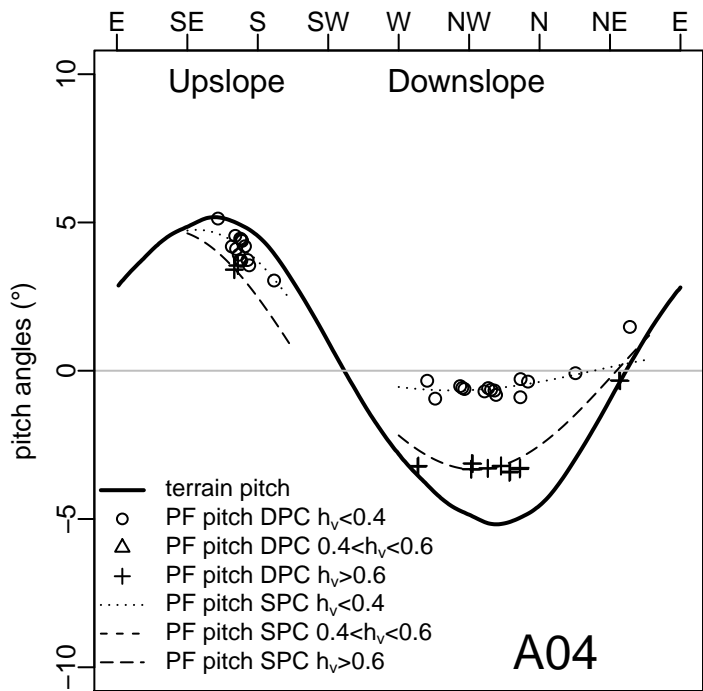
B05

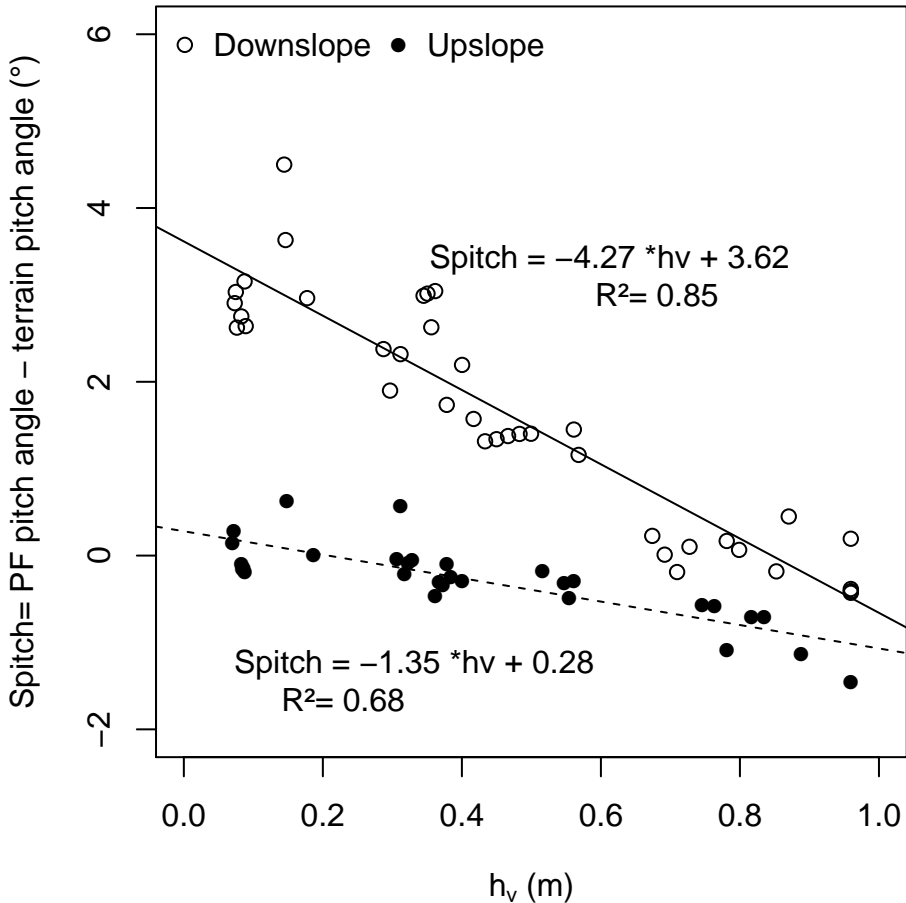


C06



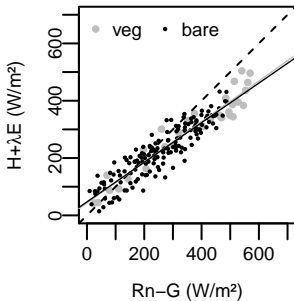






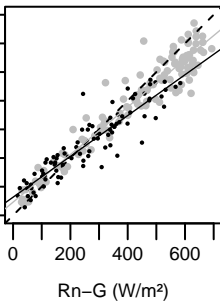
Upslope winds

A04

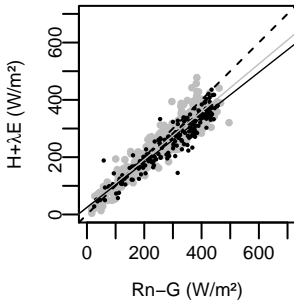


Downslope winds

$H+\lambda E$ (W/m^2)



C06



$H+\lambda E$ (W/m^2)

