POINT-BY-POINT REPLY TO THE REVIEWS:

RESPONSE TO REFEREE 2:

Dear Referee,

We appreciate your careful reading of our manuscript and the numerous insightful suggestions. Changes to the manuscript detailed below refer to the "markup copy" which is attached as a pdf to this comment. We also attached a clear copy of the manuscript as well as all figures.

Sincerely,
Alexander Röll

General comments

Referee: This study presents a study on the transpiration rates in palm oil stands of different ages. With palm oil plants becoming more and more an important feature of the tropical landscape, and data on transpiration rates of these sites being rare, I think this manuscript is an important contribution of results to the scientific community researching tropical landscapes and tropical ecosystem functioning. What is impressive about this study is the inclusion of 15 different field sites, as well as combining two different methods for measuring (evapo)transpiration rates. By including this many sites, they were able to show at what stand age transpiration does not increase anymore. Overall I think this is a well described and comprehensive study that provides valuable information to the community studying palm oil plant functioning. There are a few weaknesses to this study as well: the (eddy flux) measurements were not carried out in parallel, so we will have to assume both periods are comparable (authors could add a table for example with the meteorological data per site per measuring period). Furthermore,I think including only 4 trees per site in the sap flux measurements is not so much,although the fact that all trees have the same age in a plant will reduce the variance between trees of a stand. In addition, I think the authors can emphasize the urgency and importance of their study and research questions more.

Authors: We thank the reviewer for appreciating the high number of replicates in our study, which we consider to make our study rather unique. However, we agree that there are weaknesses due to varying measurement periods, mainly caused by difficulties of carrying out simultaneous measurements in the field in a tropical environment, e.g. regarding financial and technical aspects. We have tried to adequately cope with this problem in our study.

With regards to the relatively low number of replicates per stand (13 leaves in 4 palms), we followed an oil palm specific measurement scheme (Niu et al. 2015) that suggests relatively precise estimates of oil palm transpiration (14% sample-size related uncertainty).

During the revision, we consistently tried to sharpen the conclusions to be drawn from the results of our study, as suggested by the reviewer, and we feel that the manuscript now emphasizes the relevance of our study and research questions.

Referee: As for the presentation, I think some parts of the discussion could be written in a way that they are less of a repetition of the results, and answer to the research objectives more explicitly. Please find my more detailed comments below.

Authors: We agree that parts of the discussion were too repetitive, and we have adjusted the manuscript accordingly. We also tried to work out conclusions more clearly, and to derive a more overarching message regarding some of the potential stand-scale eco-hydrological consequences of the continuing oil palm expansion.

ABSTRACT:

Referee: P 9210 line 21: "Confronting sap flux and eddy-covariance derived water fluxes" I would use a different word than 'confronting'.

Authors: As suggested, we reworded the sentence.

Markup document (page 2):

Comparing sap flux and eddy-covariance derived water fluxes suggests that transpiration contributed 8% to evapotranspiration in the 2-year old stand and 53% in the 12-year old stand, indicating variable and substantial additional sources of evaporation, e.g. from the soil, the ground vegetation and from trunk epiphytes

Referee: P 9211 line 4-6: I do not understand this sentence, it's too vague.

Authors: We rephrased the sentence and tried to make it clearer.

Markup document (page 2):

The stand transpiration of some of the studied oil palm stands was as high or even higher than values reported for different tropical forests, indicating a high water use of oil palms under yet to be explained site or management conditions.

INTRODUCTION:

Referee: P 9212 line 27: Not clear to what "On the other hand" contrasts with. In line 19 you announce two possibilities: Water use can increase or decrease with age stand, and you start by listing the reasons for the latter. Then (line 25) you give reasons for expecting no difference, and in line 27 with a reason to expect differences. It's better to already mention in line 19 that there are three (increase, no difference, decrease in transpiration) rather than two different scenarios to expect. As it reads not, the 'On the other hand' in line 27 threw me off as a reader and I had to reread a couple of times.

Authors: We rephrased several lines in the respective section to separate the different possibilities more clearly.

Markup document (page 3/4):

Water use patterns over a gradient of plantation age to our knowledge have not yet been studied for oil palms. Water use could increase or decline with increasing stand age or could remain relatively stable from a certain age. Reasons for declining water use at a certain age include decreasing functionality of trunk xylem tissue with increasing age due to the absence of secondary growth in monocot species (Zimmermann, 1973), a variety of other hydraulic limitations (see review of dicot tree studies in Ryan et al., 2006) and increased hydraulic resistance due to increased pathway length with increasing trunk height (Yoder et al., 1994). However, for Mexican fan palms (Washingtonia robusta Linden ex André H Wendl.), no evidence of increasing hydraulic limitations with increasing palm height was found (Renninger et al., 2009). Reasons for potentially increasing water use in older plantations e.g. include linearly increasing oil palm trunk height with increasing palm age (Henson and Dolmat, 2003). As trunk height and thus volume increase, internal water storages probably also increase, possibly enabling larger (i.e. older) oil palms to transpire at higher rates (Goldstein et al., 1998; Madurapperuma et al., 2009). Additionally, increased stand canopy height is expected to result in an enhanced turbulent energy exchange with the atmosphere, i.e. a closer coupling of transpiration to environmental drivers, which can facilitate higher transpiration rates under optimal environmental conditions (Hollinger et al., 1994; Vanclay, 2009). The mentioned reasons for possibly increasing and decreasing water use with increasing plantations age, respectively, could also partly outbalance each other, or could be outbalanced by external factors (e.g. management related), potentially leading to no clear trend of oil palm transpiration over plantation age.

Referee: P 9213line 15: Although I think objective 2 is interesting, it's not made clear from the discussion before why we need to know the ratio between evapo-transpiration and transpiration.

Authors: We added a sentence to the first paragraph to highlight why this knowledge is important.

Markup document (page 2/3):

Oil palm (Elaeis guineensis Jacq.) has become the most rapidly expanding crop in tropical countries over the past decades, particularly in South East Asia (FAO, 2014). Asides from losses of biodiversity and associated ecosystem functioning (e.g. Barnes et al., 2014), potentially negative consequences of the expansion of oil palm cultivation on components of the hydrological cycle have been reported (e.g. Banabas et al., 2008). Only few studies have dealt with the water use characteristics of oil palms so far (Comte et al., 2012). Available evapotranspiration estimates derived from micrometeorological or catchment-based approaches range from 1.3 to 6.5 mm day^{-1} for different tropical locations and climatic conditions (e.g. Radersma and Ridder, 1996; Henson and Harun, 2005). However, various components of the water cycle under oil palm yet remain to be studied for a convincing hydrological assessment of the hydrological consequences of oil palm expansion, e.g. regarding the partitioning of the central water flux of evapotranspiration into transpirational and evaporative fluxes. Also, to our knowledge, influences of site or stand characteristics on oil palm water use have not yet been addressed.

Referee: P 9213line 21: "It assesses potential hydrological consequences of large-scale oil palm expansion on main components of the water cycle." Your results and Discussion underdeliver on this, you do not scale this to landscape scale or discuss the consequences of expansion of oil palm plants for the region. So better not to promise this in the introduction. Alternatively you could re-write the Discussion so it can incorporate such an assessment.

Authors: We both adjusted the sentence as not to over-promise and additionally tried to expand parts of discussion and conclusions with respect to potential hydrological consequences of oil palm expansion as not to under-deliver.

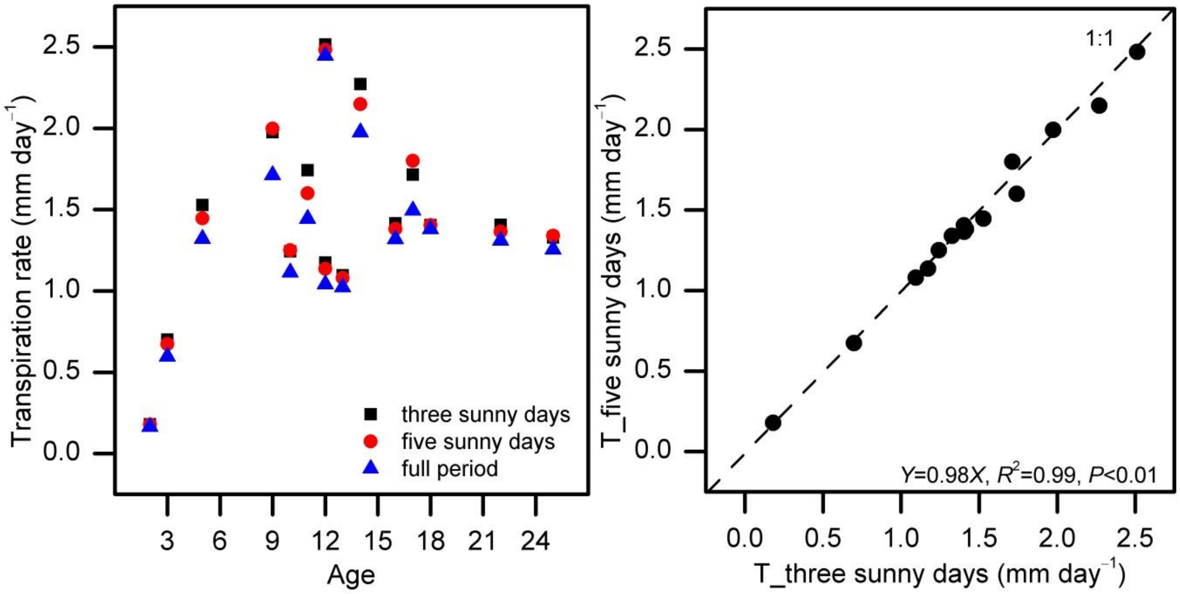
Markup document (page 4):

It assesses some of the potential hydrological consequences of oil palm expansion on main components of the water cycle at the stand level.

METHODS:

Referee: P 9215 line 16: Why use three sunny days and not the average of five days? Would that make a difference and have you tried comparing how important the inclusion of three or five (or four or six) sunny days is?

Authors: We used the average of three sunny days rather than just one sunny day in order to make the results less susceptible to e.g. to extreme values or random events. While the reviewer is right that we could have also used the average of e.g. five sunny days, data series from some of the 15 sites (as well as from 24 other, non-oil palm sites in the study region, which will be presented in further publications) were limited and partly encompassed only relatively few sunny days. Exploratory analyses at the beginning of the data analysis process showed, that absolute values were very similar when using e.g. 3, 5 or 7 sunny days. Even when using the averages of the complete data series (usually about three weeks per site), the relative differences among the 15 sites were very similar to when using the three sunny day approach. Based on our analysis, we are confident that three sunny days constitute a sufficient amount. The first figure below shows the absolute transpiration values of the 15 stands derived from using three and five sunny days and all available days, respectively. The second figure shows the very close linear relationship (R^2=0.99, $P<0.01$) between the values derived from three and five sunny days, respectively.



Referee: P 9215 line 22: Are the values behind the _ standard errors or standard deviations? Please indicate with SD or SE.

Authors: We now indicate that this is the standard deviation.

Markup document (page 6):

We chose days with a daily integrated radiation of more than 17 MJ m−2 day−1 and an average daytime VPD of more than 1.1 kPa; respective averages (mean ± SD) of all days included in the analysis were 20.3 ± 2.6 MJ m−2 day−1 and 1.6 ± 0.3 kPa (also see Table 1).

Referee: P 9215 line 27: How was palm height measured?

Authors: We included how palm height was measured into the respective sentence, as well as a reference to a more detailed description of stand variable measurements.

Markup document (page 6):

For each sample palm, trunk height to the youngest leaf (m) and diameter at breast height (cm) were measured (see Kotowska et al., 2015 for detailed methodology) and the number of leaves per palm was counted.

Referee: P9216 line 21: This reads like a repetition of the sap flux measurements mentioned under part 2.2?

Authors: We eliminated the repetitive part from this section.

Referee: P9216 line 24: Similarly here, it's like you are describing the measurements again, and therefore repeating what you mentioned in the previous paragraph. I would suggest shortening this part and focusing on what's important: The error in both measurements, and why it gives you confidence that the difference will show the contribution of the soil and other vegetation. The description of this measurement now reads as if it was added to the original paragraph in an afterthought.

Authors: We eliminated the repetitive part from the section and now focus more exclusively on the potential measurement errors.

Markup document (page 7):

To estimate the contribution of stand transpiration to total evapotranspiration, we confronted sap flux derived transpiration rates with eddy covariance derived evapotranspiration rates. As described in Niu et al. (2015), our methodological approach for estimating sap flux is associated with sample size related measurement errors of about 14%. The eddy covariance measurements were carried out in carefully-chosen and well-suited locations and focused on daytime observations only, when estimation uncertainties are commonly low (< 30%, Richardson et al., 2006). The observed differences between evapotranspiration and transpiration estimates presented in this study are thus likely largely due to natural rather than methodological reasons.

RESULTS:

Referee: P9219 line16: this non-significant relationship is that per site or with all the data from all the sites together? Can you clarify?

Authors: It is using the respective 3-sunny-day averages from all sites. We now explain this more clearly in the respective section to separate this analysis (mainly spatial variability) more clearly from the analysis of the temporal (i.e. day-to-day) variability of oil palm transpiration.

Markup document (page 10):

However, three medium-aged stands (PTPN6, BO5, and HO2) that showed increased sap flux densities and leaf and palm water use rates also had higher stand transpiration rates, between 2.0 and 2.5 mm day^{-1}. Potentially, this could be related to differences in radiation on the respective three sunny days that were chosen for the analysis. However, there was no significant relationship between average water use rates on the respective three sunny days in the 15 stands and the respective average radiation (or VPD) on those days (linear regression, $P > 0.05$), i.e. observed spatial variability in transpiration among the 15 stands could not be explained by differences in weather conditions.

Referee: P9219 line22: 'possibly indicate a slight decline'. That sounds quite uncertain.

Authors: We have removed the sentence from the section.

Markup document (page 10):

As for the leaf- and palm-level water use rates, a Hill function explained the relationship between stand transpiration and stand age ($R^2adj = 0.45$, $P < 0.01$), but the observed scatter was high, particularly among medium aged plantations.

Referee: For the rest of paragraph 3.2: a lot of results are given in the text, why not summarize them in a table or a figure? That would make it easier to refer to later in the Discussion as well.

Authors: We agree that a summary table is very helpful and added a table summarizing the main results for all 15 stands (Table 2). It gives an overview of how leaf and palm water use as well as stand transpiration could be explained by the variables number of plantation age and stand sapwood area; the table provides results for both the linear fit and using the frequently mentioned Hill function.

We added another table (Table 3), which presents the same results as Table 2, but only for 12 of the 15 stands, i.e. excluding the three stand with much higher water use (PTPN6, BO5, and HO2).

Markup document: Tables 2 and 3 on pages 30 and 31

DISCUSSION

Referee: P9221 line13: I actually don't think the observed range compares that well with the one you mention from the Acacia plantation. Yes, for the other studies you refer to, but the Acacia plants seem quite higher on average. They are in the same order of magnitude, but 3.9 mm a day is a lot higher than 2.5 mm a day. So I would leave the Cienciala study out of the list of comparable rates.

Authors: We removed the value of the 'high density' Acacia plantation from the text and adjusted the passage accordingly.

Markup document (page 12):

Among 13 studied productive oil palm stands (i.e. > 4 years old) stand transpiration rates varied more than two-fold. The observed range (1.1–2.5 mm day^{-1}) compares to transpiration rates derived with similar techniques in a variety of tree-based tropical land-use systems, e.g. an Acacia mangium plantation on Borneo (2.3mm day^{-1} for stands of relatively low density, Cienciala et al., 2000), cacao monocultures and agroforests with varying shade tree cover on Sulawesi (0.5–2.2 mm day^{-1}, Köhler et al., 2009, 2013) and reforestation and agroforestry stands on the Philippines and in Panama (0.6–2.5 mm day^{-1}, Dierick and Hölscher, 2009; Dierick et al., 2010).

Referee: P9222 line1-13: This could be explained more explicit and why it is of interest to your research objectives. Also, you seem to have more replicates in the medium aged group, how do you know if the variability in this group is not a consequence of having more replicates, rather than the sites being more variable (Would have more replicates in the older and younger stands not have shown a similar variance in those age categories?)

Authors: We agree with the reviewer that this could merely be an issue of higher replication in the medium aged group, and we adjusted the section accordingly as not to over-interpret our results among the 20-25 year-old studied plantations.

Markup document (page 10):

As for the leaf- and palm-level water use rates, a Hill function explained the relationship between stand transpiration and stand age ($R^2adj = 0.45$, $P < 0.01$), but the observed scatter was high, particularly among medium aged plantations.

Referee: P9223 line 2-7: It would be good to be more explicit in how you think the management would influence evapo-transpiration or transpiration. What would be the mechanics behind it? Different soil structures because of higher maintenance intensity? Would fertilized palms open their stomata more? Also the trade- off could be highlighted more, I think that is actually an interesting part of the results and discussion.

Authors: We agree that the relationship between water use and management intensity is highly interesting and tried to discuss in more detail how they might be interrelated. However, to our knowledge no hard data is available yet for oil palms, i.e. the character of this discussion remains partly speculative.

Markup document (page 13):

The remaining unexplained variability as well as the high water use rates in the three mentioned stands could be related to differences in site and soil characteristics. However, all studied stands were located in comparable landscape positions (i.e. upland sites of little or medium inclination) and on similar mineral soils, i.e. loam or clay Acrisols of generally comparable characteristics (Allen et al., 2015; Guillaume et al., 2015). Differences in management intensity could also contribute to the remaining unexplained variability of stand transpiration rates over age. E.g., on P-deficient soils such as the Acrisols of our study region (Allen et al., 2015), fertilization can greatly increase oil palm yield (Breure, 1982) and thus total primary productivity, which could consequently lead to a higher water use of oil palms. Accordingly, the highest observed transpiration value in our study came from a stand in an intensively and regularly fertilized, high yielding commercial plantation. Thus, there may be a trade-off between management intensity, and hence yield, on the one hand, and water use of oil palms on the other hand. This trade-off is of particular interest in the light of the continuing expansion of oil palm plantations (FAO, 2014) and increasing reports of water scarcity in oil palm dominated areas (Obidzinski et al., 2012; Larsen et al., 2014)

Referee: P9223 line 9-15: You repeat the results first, which is not bad per se, but I think you can write the point you are trying to make a bit ‘snappier’.

Authors: We shortened the respective section and tried to make it less repetitive while putting a stronger focus on the immediate conclusions to be drawn.

Markup document (page 14):

Our eddy-covariance derived evapotranspiration estimates of 2.8 and 4.7 mm day−1 (on sunny days, in 2- and 12-year old stands, respectively) compare very well to the range reported for oil palms in other studies: For 3–4 year old stands in Malaysia, eddy-covariance derived values of 1.3 mm day−1 and 3.3–3.6 mm day−1 were reported for the dry and rainy season, respectively (Henson and Harun, 2005). For mature stands, a value of 3.8 mm day−1 was given, derived by the same technique (Henson, 1999). Micrometerologically-derived values for 4–5 year old stands in Peninsular India were 2.0–5.5 mm day−1 during the dry season (Kallarackal et al., 2004). A catchment-based approach suggested values of 3.3–3.6 mm day−1 for stands in Malaysia between 2 and 9 years old (Yusop et al., 2008); evapotranspiration rates derived from the Penman-Monteith equation and published data for various stands were 1.3–2.5 mm day−1 in the dry season and 3.3–6.5 mm day−1 in the rainy season (Radersma and Ridder, 1996). The values reported in most available studies as well as our values overlap in a corridor from about 3 mm day−1 to about 5 mm day−1; this range compares to evapotranspiration rates reported for rainforests in South East Asia (e.g. Tani et al., 2003a; Kumagai et al., 2005). Considering that oil palm stands e.g. have much lower stand densities and biomass per hectare than natural tropical forests (Kotowska et al., 2015), this indicates a quite high evapotranspiration from oil palms at both the individual and the stand level. Additionally to the previously discussed relatively high water use of oil palms under certain site or management conditions, the high evapotranspiration from oil palm can be explained by substantial additional water fluxes to the atmosphere. These fluxes (i.e. the differences between evapotranspiration and transpiration estimates) were substantial in both the 2-year old and the 12-year old oil palm stand, i.e. 2.6 and 2.2 mm day−1, respectively.

Referee: Overall, I think that the paragraph 4.2 repeats a lot of results and compares them with other studies without making a clear statement or conclusion. The Discussion, in my opinion, is the place to put the results in context. What do these results mean how we think of how these sites function in the tropical landscape? The answer to that question remains quite implicit like this.

Authors: We tried to consider this suggestion of the reviewer and rewrote the section, shortening the repetitive parts and trying to derive more clear, over-arching conclusions from the presented results of our study and the discussed other studies.

Markup document (page 16):

Generally, our comparison of eddy-covariance derived evapotranspiration and sap-flux derived transpiration suggests significant other water fluxes to the atmosphere than transpiration (e.g. from evaporation) that are still marginal during the morning hours, reach their peak at the time VPD peaks and are extremely sensitive to decreasing VPD in the afternoon. In our study, transpiration amounted to only 8% and 53% of evapotranspiration in the two year-old and the 12 year-old oil palm stand, respectively, which is lower than values reported e.g. for mature coconut stands (68%, Roupsard et al., 2006) and rainforests in Malaysia (81–86%, Tani et al., 2003b). The low relative contribution of palm transpiration to total evapotranspiration in oil palm stands could be due to relatively high water fluxes from evaporation, e.g. after rainfall interception. Interception was reported to be substantially higher in oil palm stands in the study region (28%, Merten et al., in revision) than e.g. in rainforests in Malaysia (12–16%, Tani et al., 2003b) and Borneo (18%, Dykes, 1997). The high water losses from interception paired with the relatively high water use of oil palms and the consequent high total evapotranspirational fluxes from oil palm plantations could contribute to reduced water availability at the landscape level in oil palm dominated areas, e.g. during pronounced dry periods (Merten et al., in revision).

Referee: P9226 line 27: I don't think the hysteresis is that unusual, and you give the examples before, that this actually happens in other vegetation types as well. So I would remove the word 'unusual'.

Authors: We followed the advice of the reviewer and removed the word.

Markup document (page 18):

A contribution of stem water storage to transpiration in the morning could be another potential explanation (Waring and Running, 1978; Waring et al., 1979, Goldstein et al., 1998). It could explain the early peak followed by a steady decline of transpiration regardless of VPD and radiation patterns, the decline being the consequence of eventually depleted trunk water storage reservoirs. Other (palm) species were reported to have substantial internal trunk water storage capacities (e.g. Holbrook and Sinclair, 1992; Madurapperuma et al., 2009), which can contribute to sustain relatively high transpiration rates despite limiting environmental conditions (e.g. Vanclay, 2009).

Referee: P9228line 1-8: This reads as an afterthought to the previous paragraph, better to integrate it.

Authors: As suggested, we integrated the mentioned paragraph into the previous one.

Markup document (page 18/19):

At the day-to-day scale, in all 15 oil palm stands, the response of water use rates particularly to changes in VPD seemed 'buffered', i.e. near-maximum daily water use rates were reached at relatively low VPD, but better environmental conditions for transpiration (i.e. higher VPD) did not induce strong increases in water use rates (i.e. 1.2-fold increase in water use for a two-fold increase in VPD). Likewise, for both photosynthesis rates (Dufrene and Saugier, 1993) and water use rates (Niu et al., 2015) of oil palm leaves, linear increases with increasing VPD were reported at relatively low VPD, until a certain threshold (1.5–1.8 kPa) was reached, after which no further increases in photosynthesis and water use rates, respectively, occurred. For tropical tree and bamboo species, more sensitive responses to fluctuations in VPD, i.e. 1.4- to 1.7-fold increases and more than two-fold increases, respectively, have been reported (e.g. Köhler et al., 2009; Dierick et al., 2010, Komatsu et al., 2010). However, a similar 'levelling-off' effect of water use rates at higher VPD, as observed for the oil palm stands in our study, has been reported for Moso bamboo stands in Japan (in contrast to coniferous forests in the same region, where water use had a linear relationship with VPD, Komatsu et al., 2010). The hydraulic limitations 'buffering' the day-to-day oil palm water use response to VPD are yet to be explained. As soil moisture was non-limiting, they are likely of micrometeorological or eco-physiological nature. The early peaks of water use rates and the consequent strong hysteresis to VPD on the intra-daily level, which may point to a depletion of internal trunk water storage reservoirs early in the day as a possible reason for substantially reduced oil palm water use rates at the time of diurnally optimal environmental conditions, give some first indications of the direction that further studies could take.

Referee: For paragraph 4.3 I have the same comments as for 4.2 in general. I like how many studies you compare your results with, but what is your real message, what does this say about these sites that we need to know? I would recommend rewriting both these paragraphs in a way that this becomes clearer.

Authors: We tried to consider this suggestion of the reviewer and rewrote both sections, trying to derive over-arching conclusions from the presented results of our study and the discussed other studies rather than just enumerating the results.

Markup document: see rewritten sections 4.2 and 4.3 on pages 14-19