

Supplementary Information part 3: Testing different forest cover relationships

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Abstract

This supplementary material file compares different linear and non-linear relationships for the impact of forest cover on the change in stream flow.

1. Introduction

This supplementary material is related to ‘Generalising the impact of forest cover on streamflow from experimental data: it is not that simple. Vervoort et al.’

In this document we tested the following, which is outlined in the methods of the paper. The changes in forest cover contain both positive (forestation) and negative values (deforestation). In Zhang et al. [2], these changes were jointly analysed, assuming the effect on the change in flow was linear and the effect of removing forest cover was the same as an equivalent addition of forest cover. Here we test two variation of this approach, leading to three approaches:

1. Joint analysis and assuming a linear relationship between the change in streamflow and the change in forest cover, following Zhang et al. [2].
2. The impact of an increase in forest cover can be different from the same fractional decrease in forest cover. The question becomes how best to analyse this. One approach would be to allow a different slope and a different intercept for the decreases relative to the increases.
3. A second approach is to test the change in forest cover as a non-linear relationship in the Generalised additive model (GAM).

2. Methods

2.1. Approach 1

To estimate how the change in streamflow is affected by the change in forest cover, while considering the effects of the other variables, we applied generalised additive modelling (GAM) [1].

The general model tested is:

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$$\Delta Qf\% \sim \Delta\%forest\ cover + \sum X_i + \sum s(Z_i) + \varepsilon \quad (S1)$$

2.2. Approach 2

Deforestation is different from reforestation. This can be tested by converting all the change in forest cover data to positive values, and an additional binary column ($sign_{forestcover}$) can be included indicating whether it was a forest cover increase or decrease. In the model, the parameter for $sign_{forestcover}$ will indicate the difference in the changes in flow for increases in forest cover compared to decreases in forest cover. The disadvantage of this approach is that the relationship with forest cover becomes discontinuous at the origin (0 change in forest cover).

This results in the following model:

$$\Delta Qf\% \sim \Delta\%forest\ cover_{positive} + sign_{forestcover} + \sum X_i + \sum s(Z_i) + \varepsilon \quad (S2)$$

2.3. Approach 3

The relationship between the change in forest cover and change in streamflow is non-linear. The non-linear approach involves adding a smoothing function the change in forestry. A shrinkage spline [1] is applied to allow the non-linear effect to be removed. Because a shrinkage penalty is used, this will also test the non-linear assumption and allows the variable for forest cover to be continuous. The disadvantage of this approach is that the relationship between forest cover and change in flow is less easy to interpret, as the non-linear fit in the GAM has no direct parametric form. This leads to the following model:

$$\Delta Qf\% \sim s(\Delta\%forest\ cover) + \sum X_i + \sum s(Z_i) + \varepsilon \quad (S3)$$

2.4. Preliminary data management

First we will read in the data

We will combine the different tables, but will keep an indicator to see where the data are from.

```
Zhang_small$From <- as.numeric(Zhang_small$From)
Zhang_small$To <- as.numeric(Zhang_small$To)
Zhang_all <- bind_rows(Zhang_large, Zhang_small) %>%
  mutate(dataset = "original Zhang et al data")
```

```
new_data <- new_data %>%
  mutate(dataset = "new data")
All_data <- bind_rows(Zhang_all, new_data)
```

52 2.5. Implementing the changes to the overall data

53 The following code implements the changes described in the Supplementary
54 data part 1. However, many of the changes were implemented manually into the
55 data set. These are simply the remaining changes not implemented manually.

56 1. removing the duplicates.

```
All_data <- All_data %>%
  mutate(`Possible duplicate` =
    ifelse(is.na(`Possible duplicate`)==T,0,`Possible duplicate`),
    `Possible duplicate` = as.numeric(`Possible duplicate`)) %>%
  filter(`Possible duplicate` != 1)
```

57 2. calculating the dryness

```
# calculate dryness index
All_data <- All_data %>%
  mutate(Dryness = EO/Pa_mm)
```

58 3. remove watershed 1 (the Amazon) from the analysis

```
All_data <- All_data %>%
  filter(`Watershed #` != 1)
```

59 4. remove data set 188 and 254 Kamakia and Sambret

```
All_data <- All_data %>%
  filter(`Watershed #` != 188) %>%
  filter(`Watershed #` != 254)
```

60 5. add a column that indicates forest loss of forest gain

```
All_data <- All_data %>%
  mutate(forest_sign = ifelse(DeltaF_perc < 0, "Forest Cover Loss",
    "Forest Cover Gain"))
```

61 3. Results

62 3.1. Approach 1: linear relationship across all changes in forest cover

63 First the variable `length` is added, representing the number of years that
64 the data represents.

```

All_data2 <- All_data %>%
  mutate(Forest_Sign = ifelse(DeltaF_perc < 0,
                              "Decrease", "Increase"),
         DeltaF_perc_pos = ifelse(DeltaF_perc < 0,
                                   -1*DeltaF_perc,
                                   DeltaF_perc))

All_data2 <- All_data2 %>%
  mutate(length = To - From,
         mid_year = From + (To - From)/2)

Forest_model_all <- gam(DeltaQf_perc ~ DeltaF_perc +
  s(log10(Area_km2), k = 5, bs="ts") +
  s(Dryness, k = 10, bs="ts" ) +
  s(length, k = 35, bs="ts") +
  Precip_data_type + Assessment_technique +
  Forest_type +
  Hydrological_regime
  , data = All_data2)

#summary(Forest_model_all)
#gam.check(Forest_model_all)
#plot(model6_all)

```

Table S1: (#tab:m_all-linear) Statistical summary for the linear terms the full model

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	-4.81	16.31	-0.29	0.77
DeltaF_perc	-0.6	0.06	-10.71	0
Precip_data_typeOB	-21.4	13.23	-1.62	0.11
Precip_data_typeSG	9.36	15.17	0.62	0.54
Assessment_techniqueEA, HM	20.64	42.73	0.48	0.63
Assessment_techniqueHM	22.81	11.71	1.95	0.05
Assessment_techniquePWE	30.63	11.94	2.57	0.01
Assessment_techniquePWE, HM	17.42	43.26	0.4	0.69
Assessment_techniqueQPW	39.52	20.15	1.96	0.05
Assessment_techniqueQPW, EA	24.39	24.42	1	0.32
Assessment_techniqueSH	45.3	11.83	3.83	0
Forest_typeCF	-9.45	7.6	-1.24	0.21
Forest_typeMF	-8.05	7.56	-1.06	0.29
Hydrological_regimeSD	3.57	9.16	0.39	0.7

65 This is the baseline result as it echoes Zhang et al. [2] but in this case the
66 relationship is tested together with other variables as is discussed in the main
67 paper.

68 For this model, the focus can be on the linear variables. The variable
69 **DeltaF_perc** clearly explains the variation in the change in flow with a p-value
70 of 0. The overall model explains 49 % of the variation in the data. For compar-
71 ison across models with different structures and different variables, the Aikaike
72 Information Criteria (AIC) can be used. The AIC of the model is 3181.7600577.

73 3.2. The change in forest cover converted to positive values

```
Forest_model_all2 <- gam(DeltaQf_perc ~ DeltaF_perc_pos + Forest_Sign +
  s(log10(Area_km2), k = 5, bs="ts") +
  s(Dryness, k = 10, bs="ts" ) +
  s(length, k = 35, bs="ts") +
  Precip_data_type + Assessment_technique +
  Forest_type +
  Hydrological_regime
  , data = All_data2)
#summary(Forest_model_all2)
```

Table S2: (#tab:m_all2-linear) Statistical summary for the linear terms the alternative model where the change is forestry is all positive

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	14.05	20	0.7	0.48
DeltaF_perc_pos	0.29	0.1	2.9	0
Forest_SignIncrease	-51.91	7.79	-6.67	0
Precip_data_typeOB	-19.43	14.56	-1.33	0.18
Precip_data_typeSG	4.43	17.22	0.26	0.8
Assessment_techniqueEA,	18.4	46.56	0.4	0.69
HM				
Assessment_techniqueHM	21.99	13.63	1.61	0.11
Assessment_techniquePWE	27.8	13.85	2.01	0.05
Assessment_techniquePWE,	17.58	46.6	0.38	0.71
HM				
Assessment_techniqueQPW	25.71	22.18	1.16	0.25
Assessment_techniqueQPW,	33.3	26.36	1.26	0.21
EA				
Assessment_techniqueSH	38.7	13.25	2.92	0
Forest_typeCF	-12.71	8.25	-1.54	0.12
Forest_typeMF	-7.05	8.36	-0.84	0.4

	Estimate	Std. Error	t value	Pr(> t)
Hydrological_regimeSD	7.27	10	0.73	0.47

Again the focus can be on the linear variables. In this case the variable `DeltaF_perc_pos` also is important to explain the variation in the change in flow with a p-value of 0. However, the results also show that in this case, the deforestation (`Forest_Sign < 0`) has a different effect than reforestation (`Forest_Sign > 0`). In fact, in absolute terms deforestation creates a -5191 % greater effect on streamflow than reforestation (and of course deforestation creates and increase in flow and reforestation a decrease).

However, overall this model explains less of the overall variation in the data with a deviance explained of 0.45 and an AIC of 3227.3976077.

3.3. Assuming the change in forest cover is non-linear

The difference between reforestation and deforestation might suggest that the relationship between the change in forest cover and change in stream flow is non-linear. This is tested in the model where the change in forest cover is considered non-linear. The number of knots was decided based on checking the edf value relative to the apparent knots `k` with the procedure `gam.check()` in the package `mgcv` [1].

```
Forest_model_nonlin <- gam(DeltaQf_perc ~ s(DeltaF_perc, k=10, bs = "ts") +
  s(log10(Area_km2), k = 5, bs="ts") +
  s(Dryness, k = 10, bs="ts") +
  s(length, k = 35, bs="ts") +
  Precip_data_type + Assessment_technique +
  Forest_type +
  Hydrological_regime
  , data = All_data2)
#summary(Forest_model_nonlin)
```

Table S3: (`#tab:m_nonlin-smooth`) Statistical summary for the smooth terms for the model that considers the change in forest cover to be a non-linear variable

	edf	Ref.df	F	p-value
s(DeltaF_perc)	4.14	9	13.2	0
s(log10(Area_km2))	0.74	4	0.74	0.04
s(Dryness)	4.73	9	2.4	0
s(length)	4.68	34	0.26	0.08

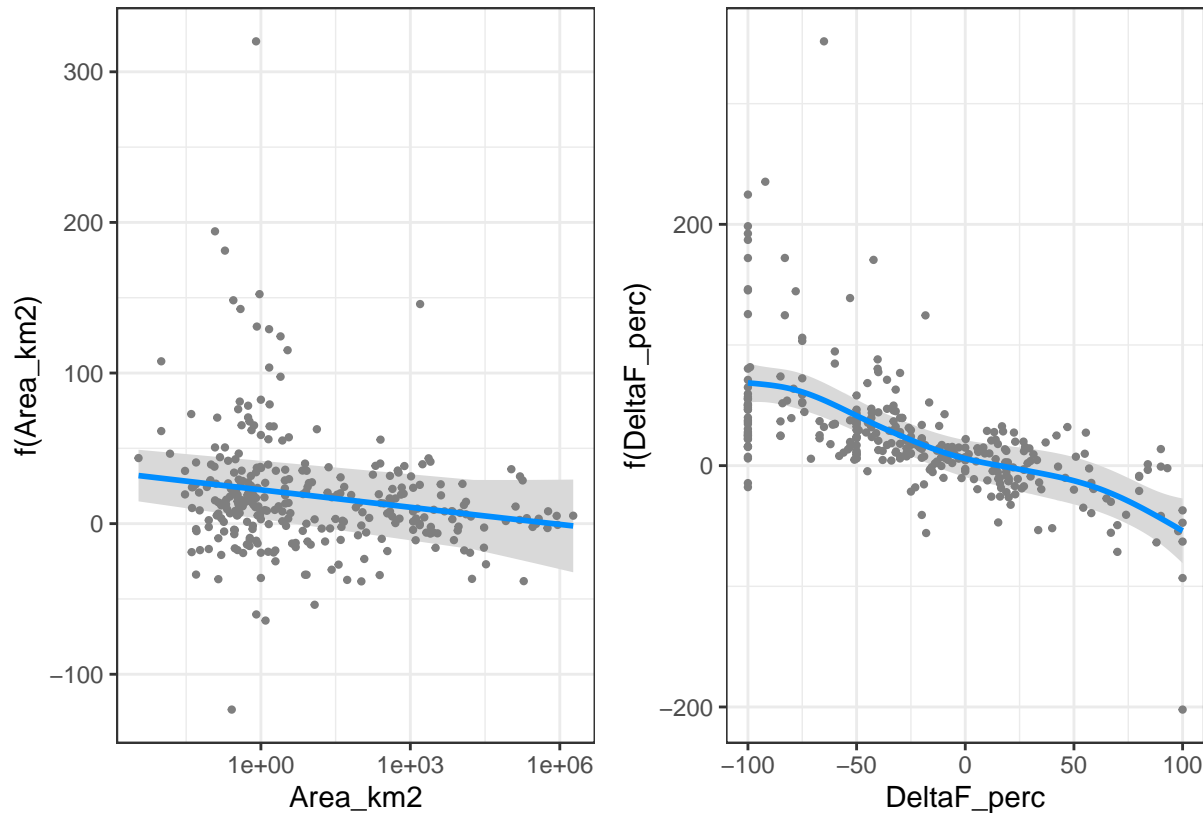
In this case, the non-linear terms of the model need to be checked, which shows that once again, changes in forest cover impact changes in flow as indicated by the p-value of 0. The total deviance explained for the model is 0.5 and

93 the model has an AIC of 3182.1088731. These performance statistics are similar
 94 to the first (baseline) model.

95 One thing that is of interest is the fact that while a non-linear relationship
 96 between the change in forest cover and the change in streamflow was conceptu-
 97 alised, the actual relationship turns out to be linear. This can be shown from
 98 the plot and by running `gam.check`.

```
D <- visreg(Forest_model_nonlin, "DeltaF_perc", gg = T, plot = T) + theme_bw()
A <- visreg(Forest_model_nonlin, "Area_km2", gg = T, plot = T) + theme_bw() +
  scale_x_log10()

(A + D)
```

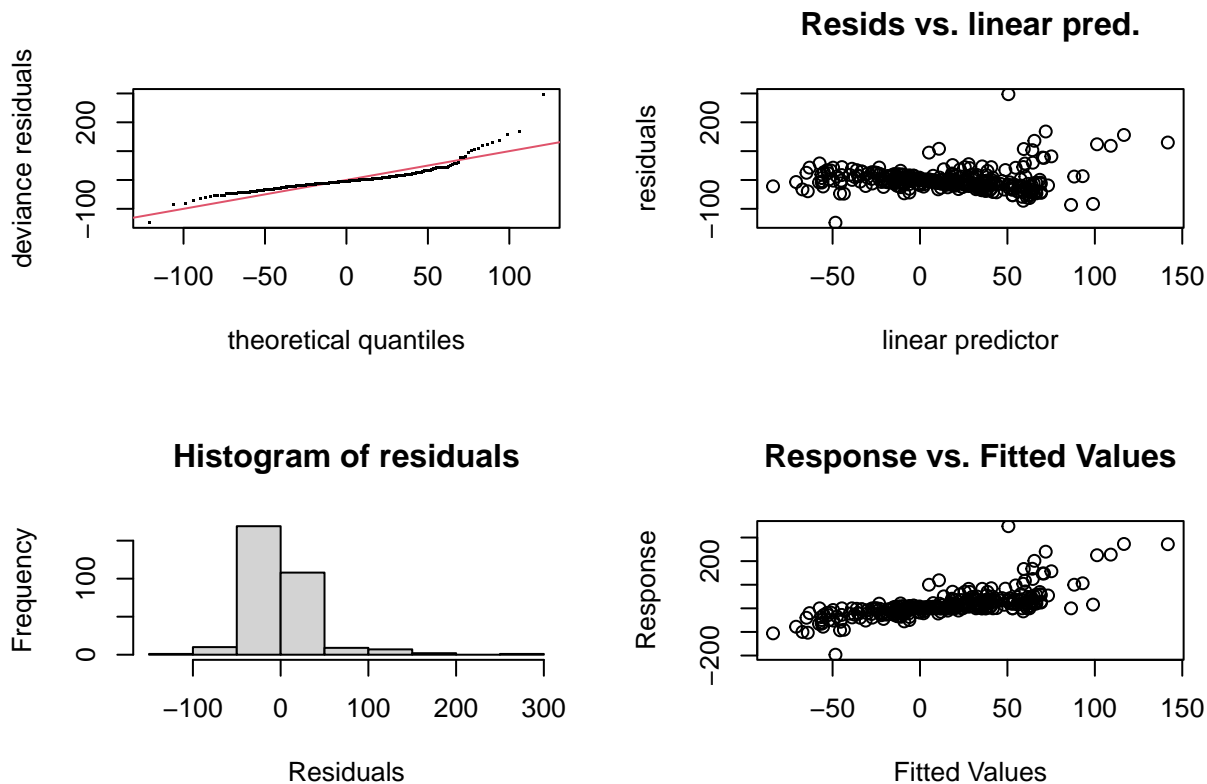


99 The procedure `gam.check` highlights that the p-value of the Basis dimension
 100 check of the smooth on `DeltaF_perc` is very small and the actual edf is close to
 101 1 suggesting a linear relationship, similar to the smooth on `log10(Area_km2)`.
 102

103 The residual analysis shows that including this non-linearity makes no differ-
 104 ence in terms of the distribution of the residuals. While there is some remaining
 105 weak trend in the data, the overall distribution of the residuals is approximately

106 normal.

```
par(mfrow= c(2,2))
gam.check(Forest_model_nonlin)
```



107

```
108 ##
109 ## Method: GCV   Optimizer: magic
110 ## Smoothing parameter selection converged after 11 iterations.
111 ## The RMS GCV score gradient at convergence was 0.0003791486 .
112 ## The Hessian was positive definite.
113 ## Model rank = 69 / 69
114 ##
115 ## Basis dimension (k) checking results. Low p-value (k-index<1) may
116 ## indicate that k is too low, especially if edf is close to k'.
117 ##
118 ##           k'   edf k-index p-value
119 ## s(DeltaF_perc) 9.00 4.14  0.91  0.075 .
120 ## s(log10(Area_km2)) 4.00 0.74  0.95  0.140
```



```

121 ## s(Dryness)          9.00  4.73    0.93   0.135
122 ## s(length)           34.00  4.68    0.93   0.110
123 ## ---
124 ## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

125 References

- 126 [1] S. Wood. *Generalized additive models: an introduction with R*. CRC Press,
127 Boca Raton, FL, 2006. ISBN 978-1584884743.
- 128 [2] Mingfang Zhang, Ning Liu, Richard Harper, Qiang Li, Kuan Liu, Xiao-
129 hua Wei, Dingyuan Ning, Yiping Hou, and Shirong Liu. A global review
130 on hydrological responses to forest change across multiple spatial scales:
131 Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology*, 546:44–59, 2017. ISSN 0022-1694. doi: <https://doi.org/10.1016/j.jhydrol.2016.12.040>. URL <http://www.sciencedirect.com/science/article/pii/S0022169416308307>.
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