`rbiprobit`: Recursive bivariate probit estimation and decomposition of marginal effects

Mustafa Coban

Institute for Employment Research, Germany

mustafa.coban@iab.de github.com/cobanomics

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Motivation

Effects of interest

1. What we want
   - Estimate: Effect of binary or treatment variable on binary outcome variable
   - Treatment variable itself is endogenous
   - Unobservables may correlate with treatment and outcome equation
   - Compute average treatment effect
   - Compute average marginal effect of independent variables
2. What doesn't work:
   - `margins` gives incorrect treatment effect using `biprobit`
   - `margins` gives incorrect average marginal effect using `biprobit`
   - `ivprobit` inapproriate; treatment variable is binary
3. What we need
   - Correct Estimation of a recursive bivariate probit model (RBPM)
   - Considering recursive nature of the model for postestimation commands

Contribution

A new Stata package

- `rbiprobit` estimates RBPMs like `biprobit` or `cmp`
  - allows weights (`pw,fw,iw`)
  - provides various variance estimators (`vce`)
  - `bootstrap`, `jackknife`, and `svy` prefix are allowed
- `rbiprobit` accounts for recursive nature in postestimation
- Postestimation commands enable
  - Correct predictions
  - Computation of different treatment effects
  - Decomposition of average marginal effects of independent variables
  - Standard errors using the delta method or bootstrapping

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Recursive bivariate probit model

The Model

A structural model with endogenous explanatory treatment variable y_2

$$y_1^\star = x'\beta + \alpha y_2 + u_1 \quad , y_1 = 1\left[y_1^\star > 0\right] \tag{1}$$

$$y_2^\star = z'\gamma + u_2 \quad , y_2 = 1\left[y_2^\star > 0\right] \tag{2}$$

$$\text{with } \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} \sim \mathcal{N}\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix}\right]$$

- correlation between u_1 and u_2 induces endogeneity
- parametric distribution assumption is bivariate normality
- x' and z' can share some or all independent variables
- Greene (2018) notes that endogenous nature of y_2 can be ignored
- Han and Lee (2019): estimates are at best weakly identified if $\boldsymbol{x} = \boldsymbol{z}$

Recursive bivariate probit model

Treatment Effects: ATE and ATET

1. Average treatment effect (ATE)

$$\text{ATE} = \Phi(x'\beta + \alpha) - \Phi(x'\beta)$$

- Ceteris-paribus scenario over full sample
- Effect of discrete change in treatment holding all other observed and unobserved variables constant

Recursive bivariate probit model

Treatment Effects: ATEC

2. Average treatment effect on conditional probability of outcome success (ATEC)

$$\text{ATEC} = \frac{\Phi_2(x'\beta + \alpha, z'\gamma, \rho)}{\Phi(z'\gamma)} - \frac{\Phi_2(x'\beta, -z'\gamma, -\rho)}{\Phi(-z'\gamma)}$$

- Accounts for selection on unobservables
- Utilizes conditional probabilities of the outcome $\Pr(y_{1i} = 1 | y_{2i} = s)$ for $s = 0, 1$ over full sample.
- Effect of a discrete change in treatment, holding only the observed variables constant
- Imposing no constraint on ρ to account for changes in unobserved variables as a consequence of the treatment
- ATEC collapses to ATE if $\rho = 0$

Decomposition of Marginal Effects

Joint and Conditional Probabilities

- Independent variable d appears in both x' and z'
- Decomposition of total marginal effects on the probabilities (except marginal probabilities) are then
    1. Continuous Variables (see Greene, 2018)

$$\text{ME} = \frac{\partial \Pr}{\partial \begin{pmatrix} x_d \\ z_d \end{pmatrix}} = \underbrace{\frac{\partial \Pr}{\partial x_d}}_{\text{direct effect}} + \underbrace{\frac{\partial \Pr}{\partial z_d}}_{\text{indirect effect}}$$

    2. Discrete Variables (see Hasebe, 2013; Edwards et al., 2019)

$$\text{ME} = \underbrace{\left[\Pr|_{x_d=1} - \Pr|_{x_d=0}\right]}_{\text{direct effect}} + \underbrace{\left[\Pr|_{z_d=1} - \Pr|_{z_d=0}\right]}_{\text{indirect effect}}$$

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Basic Syntax

`rbiprobit` *depvar* [=] [*indepvars*] [*if*] [*in*] [*weight*]
, `endogenous`(*depvar_en* [=] [*indepvars_en*] [, *enopts*]) [*options*]

- `depvar` and `depvar_en` have to be 0/1 variables
- *depvar_en* automatically added to outcome equation as factor-variable
- Factor variables and time-series operators allowed
- `bootstrap`, `jackknife`, and `svy` prefix are allowed
- Variance estimators: `robust`, `cluster robust`, `bootstrap`, ...
- Linear constraints are applicable

Postestimation Commands

probability functions

Predictions

`predict` [*type*] *newvar* [*if*] [*in*] [, *statistic*]

statistic

`p11`	Pr(depvar = 1, depvar_en = 1); the default
`p10`	Pr(depvar = 1, depvar_en = 0)
`p01`	Pr(depvar = 0, depvar_en = 1)
`p00`	Pr(depvar = 0, depvar_en = 0)
`pmarg1`	Pr(depvar = 1); marginal success probability for outcome eq.
`pmarg2`	Pr(depvar_en = 1); marginal success probability for treatment eq.
`pcond1`	Pr(depvar = 1 | depvar_en = 1)
`pcond2`	Pr(depvar_en = 1 | depvar = 1)
`xb1`	linear prediction for outcome eq.
`xb2`	linear prediction for treatment eq.

...

Postestimation Commands

Margins and Treatment Effects

`rbiprobit margdec` [*if*] [*in*] [*weight*] [, *response_options options*]

`rbiprobit tmeffects` [*if*] [*in*] [*weight*] [, `tmeffect(`*effecttype*`)` *options*]

rbiprobit margdec options

`effect(`*effecttype*`)`	specify type of effect; *effecttype* may be `total`, `direct`, or `indirect`; default is `total`
`predict(`*pred_opt*`)`	estimate margins for `predict`, *pred_opt* ; multiple `predict` not applicable
`dydx(`*varlist*`)`	estimate marginal effect of variables in *varlist*

...

rbiprobit tmeffects options

`tmeffect(`*effecttype*`)`	specify type of effect; *effecttype* may be `ate`, `atet`, or `atec`; default is `ate`

...

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An empirical application

independent variables

Preference for redistribution and hazard of national culture by immigrants

1. Research question
   Does the perception of immigrants as a hazard of national culture effect natives' preference for redistribution?
2. Data
   - European Social Survey (Wave 7, 2014)
   - Individual Data from the United Kingdom
   - Data adjusted for demonstration purposes
   - Sample restricted to respondents with no migration background
3. The Model
   - Binary outcome variable: `redist`
     Should the government reduce difference in income levels?
     (Agree = 1, Disagree = 0)
   - Binary treatment variable: `imcult`
     Do immigrants undermine or enrich country's cultural life?
     (Undermine = 1, Enrich = 0)

rbiprobit output table

```
. use "https://cobanomics.github.io/rbiprobit/data/ess7_uk.dta", clear
(Modified excerpt from European Social Survey Wave 7 for United Kingdom)

. global indeplist       c.age##c.age i.female i.urban educyrs rigleft i.lbf

. rbiprobit redist = $indeplist hhincdec hhmemb ///
>                  , endog(imcult = $indeplist i.pareduc imcont) nolog

Recursive Bivariate Probit Regression          Number of obs     =      1,256
                                               Wald chi2(19)     =     334.05
Log likelihood = -1120.1179                    Prob > chi2       =     0.0000

------------------------------------------------------------------------------------
                    |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
--------------------+---------------------------------------------------------------
redist              |
             imcult |
Culture undermined  |  -1.093271   .3153386    -3.47   0.001    -1.711323   -.4752184
                age |   .0415339   .0155237     2.68   0.007      .011108    .0719598
                    |
        c.age#c.age |  -.0003429   .0001435    -2.39   0.017    -.0006243   -.0000616
                    |
             female |
            Female  |  -.0292688   .0874852    -0.33   0.738    -.2007366    .1421991
                    |
              urban |
    [1] (Sub)Urban  |   .0833317   .0967068     0.86   0.389    -.1062102    .2728736
            educyrs |   .0060353   .0124718     0.48   0.628    -.0184091    .0304796
            rigleft |   .1570994   .0275802     5.70   0.000     .1030432    .2111557
                    |
                lbf |
          Employed  |  -.0546754   .1064449    -0.51   0.607    -.2633036    .1539527
           hhincdec |  -.0636975   .0172709    -3.69   0.000    -.0975479   -.0298471
             hhmemb |  -.0008141   .0409355    -0.02   0.984    -.0810461     .079418
              _cons |  -1.732201   .6640082    -2.61   0.009    -3.033633   -.4307688
--------------------+---------------------------------------------------------------
```

rbiprobit output table (con't)

```
--------------------+----------------------------------------------------------------
imcult              |
                age |   .0075091   .0164422     0.46   0.648    -.0247169    .0397352
                    |
        c.age#c.age |  -.0000784   .0001574    -0.50   0.619    -.0003869    .0002302
                    |
             female |
            Female  |   .3339391   .0884987     3.77   0.000     .1604849    .5073933
                    |
              urban |
    [1] (Sub)Urban  |  -.1769626    .100775    -1.76   0.079     -.374478    .0205528
            educyrs |  -.0586824   .0114027    -5.15   0.000    -.0810314   -.0363335
            rigleft |  -.1342447   .0219501    -6.12   0.000    -.1772661   -.0912234
                    |
                lbf |
          Employed  |  -.1640761   .1136411    -1.44   0.149    -.3868085    .0586563
                    |
            pareduc |
   Academic parent  |  -.1822516   .0965664    -1.89   0.059    -.3715182    .0070151
             imcont |  -.0794116   .0255358    -3.11   0.002    -.1294609   -.0293623
              _cons |   2.854024   .4839785     5.90   0.000     1.905444    3.802604
--------------------+----------------------------------------------------------------
           /atanrho |   .6042669   .2333532     2.59   0.010     .1469031    1.061631
--------------------+----------------------------------------------------------------
                rho |   .5400788   .1652875                       .1458554    .7862872
-------------------------------------------------------------------------------------
Wald test of rho=0: chi2(1) = 6.70549                       Prob > chi2 = 0.0096
```

- In ML estimation ρ is not directly estimated, but atanh ρ
- estimated correlation between error terms is positive and significantly different from zero
- Applying `lrmodel` would give the LR model test instead of the Wald test

The correlation parameter

Comparison: biprobit vs. rbiprobit

```
. biprobit (redist = $indeplist hhincdec i.hhincmsc)
> (imcult = $indeplist i.pareduc imcont)
```

	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
/athrho	-.0592815	.0641919	-0.92	0.356	-.1850952	.0665323
rho	-.0592121	.0639668			-.18301	.0664343

```
. rbiprobit redist = $indeplist hhincdec i.hhincmsc
> , endog(imcult = $indeplist i.pareduc imcont)
```

	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
imcult						
Culture undermined	-1.093271	.3153386	-3.47	0.001	-1.711323	-.4752184
/atanrho	.6042669	.2333532	2.59	0.010	.1469031	1.061631
rho	.5400788	.1652875			.1458554	.7862872

Explanation according to Filippini et al. (2018)

The correlation parameter in biprobit is a weighted average of the correlation parameter from rbiprobit and the coefficient on treatment variable imcult

Postestimation: Predictions

biprobit workaround

Comparison: biprobit vs. rbiprobit

```
. qui: rbiprobit redist = $indeplist hhincdec hhmemb ///
>          , endog(imcult = $indeplist i.pareduc imcont)

. predict p11_rbp, p11

. qui: biprobit (redist = $indeplist hhincdec hhmemb i.imcult) ///
>          (imcult = $indeplist i.pareduc imcont), nolog

. predict p11_bp, p11

. compare p11_rbp p11_bp

                                        ---------- difference ----------
                            count       minimum      average     maximum
------------------------------------------------------------------------
p11_rbp<p11_bp                230     -.3982587    -.2817366   -.0239254
p11_rbp=p11_bp               1025
p11_rbp>p11_bp                  1      1.49e-08     1.49e-08    1.49e-08
                       ----------
jointly defined              1256     -.3982587    -.0515919    1.49e-08
                       ----------
total                        1256
```

Incorrecte predictions after biprobit

biprobit doesn't account for recursive nature of the model, e.g. takes observed y_{2i} instead of $y_{2i} = 1\ \forall\ i$ in $\Pr(y_{1i} = 1, y_{2i} = 1)$

Postestimation: Treatment effects

atet

rbiprobit tmeffects: Average treatment effects

```
. rbiprobit tmeffects, tmeffect(ate)

Treatment effect                                Number of obs     =      1,256
Model VCE     : OIM

Expression    : Pr(redist=1), predict(pmarg1)
Effect        : Average treatment effect
dydx w.r.t.   : 1.imcult

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
         ate |   -.355684   .1156057    -3.08   0.002     -.582267    -.129101
------------------------------------------------------------------------------

. rbiprobit tmeffects, tmeffect(atec)

Treatment effect                                Number of obs     =      1,256
Model VCE     : OIM

Expression    : Pr(redist=1|imcult=1)-Pr(redist=1|imcult=0), predict(pcond1)-predict(pc
> ond10)
Effect        : Average treatment effect on conditional probability
dydx w.r.t.   : 1.imcult

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        atec |   -.017399   .0300759    -0.58   0.563    -.0763467     .0415488
------------------------------------------------------------------------------
```

Postestimation: Marginal effects

rbiprobit margdec: Average marginal effects (continuous independent variable)

```
. rbiprobit margdec, dydx(rigleft) predict(p11) effect(direct)

Average marginal effects                        Number of obs     =      1,256
Model VCE    : OIM

Expression   : Pr(redist=1,imcult=1), predict(p11)
dy/dx w.r.t. : rigleft

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     rigleft |   .0341355   .0053522     6.38   0.000     .0236452    .0446257
------------------------------------------------------------------------------

. rbiprobit margdec, dydx(rigleft) predict(p11) effect(indirect)

Average marginal effects                        Number of obs     =      1,256
Model VCE    : OIM

Expression   : Pr(redist=1,imcult=1), predict(p11)
dy/dx w.r.t. : rigleft

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     rigleft |  -.0025357    .001461    -1.74   0.083    -.0053992    .0003278
------------------------------------------------------------------------------
```

Postestimation: Marginal effects

don't use margins

rbiprobit margdec: Average marginal effects (continuous independent variable)

```
. rbiprobit margdec, dydx(rigleft) predict(p11) effect(total)

Average marginal effects                          Number of obs     =      1,256
Model VCE    : OIM

Expression   : Pr(redist=1,imcult=1), predict(p11)
dy/dx w.r.t. : rigleft

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     rigleft |   .0315997   .0047834     6.61   0.000     .0222244    .0409751
------------------------------------------------------------------------------
```

- Direct effect of `rigleft` is positive
- Indirect effect of `rigleft` is negative
- Indirect effect doesn't offset direct effect entirely

Postestimation: Plots

rbiprobit margdec and rbiprobit tmeffects: Marginsplots

- Marginsplot of total average marginal effects

```
. rbiprobit margdec, dydx(rigleft hhincdec lbf) pr(p11) eff(total)
. marginsplot
```

- Marginsplot of indirect average marginal effects

```
. rbiprobit margdec, dydx(female pareduc) pr(p10) eff(indirect)
. marginsplot
```

- Marginsplot of average treatment effect

```
. rbiprobit tmeffects, tmeffect(ate)
. marginsplot
```

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Conclusion

- `rbiprobit` is a suitable alternative for `ivprobit`
- `rbiprobit` identified even without IV (theoretically)
- Without IV: identification of `rbiprobit` decisively based on bivariate normality assumption
- `rbiprobit` takes into account recursive nature of the model in contrast to `biprobit` or `cmp`
- Three different treatment effects computable
- Decomposition of marginal effects gives insight about insignificant total marginal effects

Thank you

Version 1.1.0 available

```
ssc install rbiprobit
```

In the future, minor updates available via

```
net install rbiprobit, from("https://cobanomics.github.io/rbiprobit/")
```

github.com/cobanomics
@cobanomics
mustafa.coban@iab.de
mustafacoban.de

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Predictions of Interest

1. Joint Probabilities

$$\Pr(y_1 = 1, y_2 = 1|x, z) = \Phi_2(x'\beta + \alpha, z'\gamma, \rho)$$
$$\Pr(y_1 = 1, y_2 = 0|x, z) = \Phi_2(x'\beta, -z'\gamma, -\rho)$$
$$\Pr(y_1 = 0, y_2 = 1|x, z) = \Phi_2(-x'\beta - \alpha, z'\gamma, -\rho)$$
$$\Pr(y_1 = 0, y_2 = 0|x, z) = \Phi_2(-x'\beta, -z'\gamma, \rho)$$

2. Conditional Probabilities

$$\Pr(y_1 = 1|y_2 = 1, x, z) = \frac{\Phi_2(x'\beta + \alpha, z'\gamma, \rho)}{\Phi(z'\gamma)}$$
$$\Pr(y_2 = 1|y_1 = 1, x, z) = \frac{\Phi_2(x'\beta + \alpha, z'\gamma, \rho)}{\Phi(x'\beta + \alpha)}$$

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Predictions of Interest

3. Marginal Probabilities

$$\Pr(y_1 = 1|x) = \Phi(x'\beta + \alpha y_2)$$
$$\Pr(y_2 = 1|z) = \Phi(z'\gamma)$$

4. Unconditional Mean Function (see Blasch et al., 2019; Alrasheed, 2019)

$$\begin{aligned} E[y_1|x,z] &= \Pr(y_2 = 1|z) \cdot E[y_1|y_2 = 1, x, z] \\ &\quad + \Pr(y_2 = 0|z) \cdot E[y_1|y_2 = 0, x, z] \\ &= \Pr(y_1 = 1, y_2 = 1|x, z) + \Pr(y_1 = 1, y_2 = 0|x, z) \\ &= \Phi_2(x'\beta + \alpha, z'\gamma, \rho) + \Phi_2(x'\beta, -z'\gamma, -\rho) \end{aligned}$$

An empirical application

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Varlist of independent variables

- Independent variables common to both equations
  - Age (`age`)
  - Gender (`female`)
  - Place of residence (`urban`)
  - Years of education (`educyrs`)
  - Main activity, last 7 days (`lbf`)
  - Self-placement on political left-right scale (`rigleft`)
- Independent Variables only in treatment equation
  - At least one parent is academic (`pareduc`)
  - Frequency of contact with immigrants beyond workplace and friendships (`imcont`)
- Independent Variables only in outcome equation
  - Household income (`hhincdec`)
  - Number of household members (`hhmemb`)

Postestimation: Predictions

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biprobit workaround for joint/conditional probabilities

```
. qui: rbiprobit redist = $indeplist hhincdec hhmemb ///
>         , endog(imcult = $indeplist i.pareduc imcont)

. predict p11_rbp, p11

. qui: biprobit (redist = $indeplist hhincdec hhmemb i.imcult) ///
>         (imcult = $indeplist i.pareduc imcont), nolog

. replace redist = 1
(982 real changes made)

. replace imcult = 1
(230 real changes made)

. predict p11_bp, p11

. compare p11_rbp p11_bp

                                        ---------- difference ----------
                            count       minimum      average     maximum
------------------------------------------------------------------------
p11_rbp=p11_bp               1255
p11_rbp>p11_bp                  1      1.49e-08     1.49e-08    1.49e-08
                       ----------
jointly defined              1256             0     1.19e-11    1.49e-08
                       ----------
total                        1256
```

Postestimation: Treatment effects

back

`rbiprobit tmeffects`: Average treatment effect on the treated

$$\text{ATET} = \Phi\left(\frac{x_i'\beta + \alpha - \rho z_i'\gamma}{\sqrt{1-\rho^2}}\right) - \Phi\left(\frac{x_i'\beta - \rho z_i'\gamma}{\sqrt{1-\rho^2}}\right) \quad \forall\ y_{2i} = 1$$

- Ceteris-paribus scenario over sub-sample of treated
- Effect of discrete change in treatment on the conditional probability $\Pr(y_{1i} = 1 | y_{2i} = 1)$

```
. rbiprobit tmeffects, tmeffect(atet)

Treatment effect                                Number of obs     =      1,026
Model VCE     : OIM

Expression    : normal(redist=1|imcult=1) - normal(redist=1|imcult=0)
Effect        : Average treatment effect on the treated
dydx w.r.t.   : 1.imcult

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        atet |  -.2459238   .0662172    -3.71   0.000    -.3757072   -.1161404
------------------------------------------------------------------------------
```

Postestimation: Marginal effects

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Incorrect standard errors using `margins`

```
. margins, dydx(rigleft) predict(p11)

Average marginal effects                        Number of obs     =      1,256
Model VCE    : OIM

Expression   : Pr(redist=1,imcult=1), predict(p11)
dy/dx w.r.t. : rigleft

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     rigleft |   .0315997   .0045339     6.97   0.000     .0227135     .040486
------------------------------------------------------------------------------

. rbiprobit margdec, dydx(rigleft) predict(p11) effect(total)

Average marginal effects                        Number of obs     =      1,256
Model VCE    : OIM

Expression   : Pr(redist=1,imcult=1), predict(p11)
dy/dx w.r.t. : rigleft

------------------------------------------------------------------------------
             |            Delta-method
             |      dy/dx   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     rigleft |   .0315997   .0047834     6.61   0.000     .0222244    .0409751
------------------------------------------------------------------------------
```